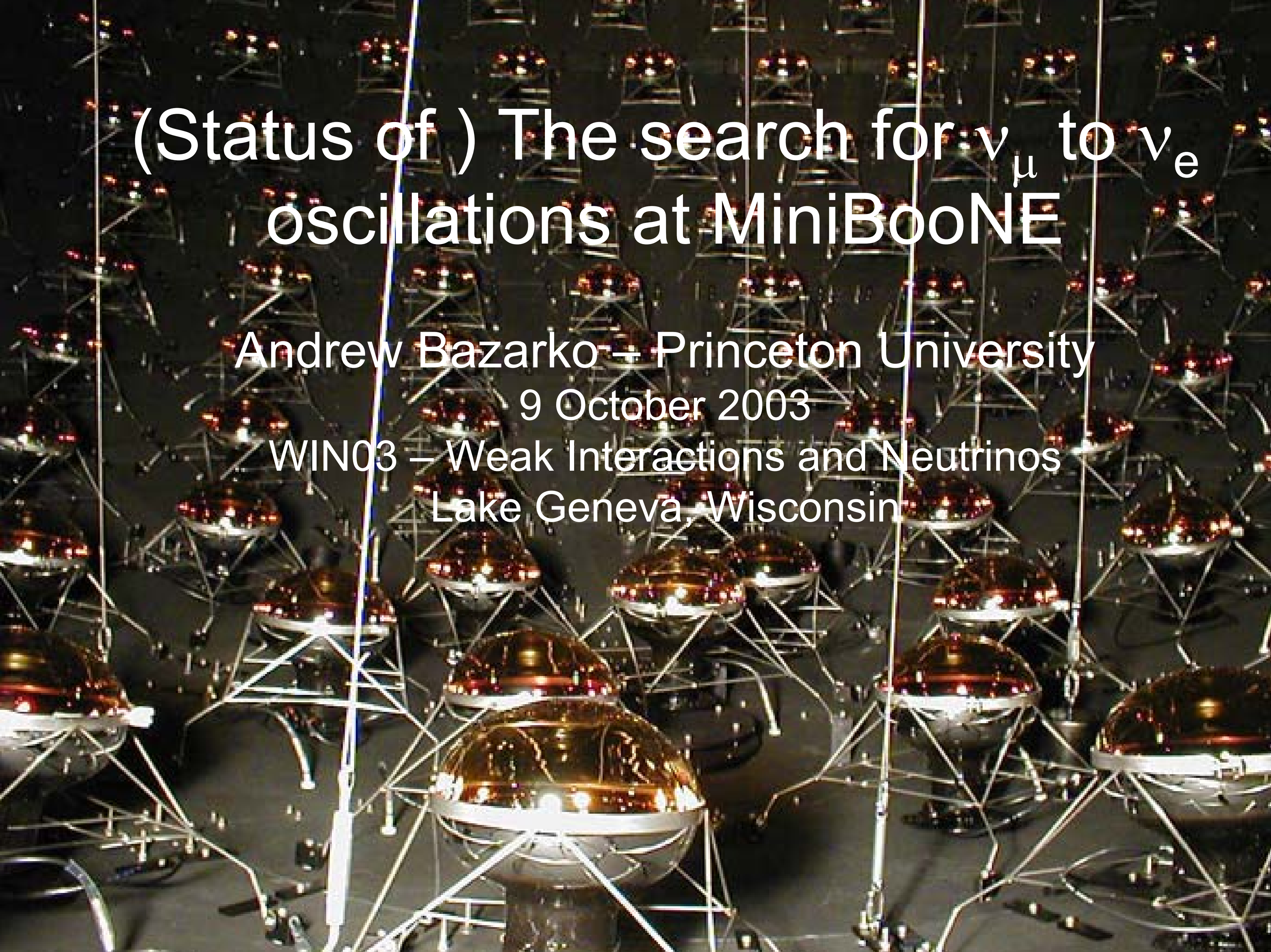
(Status of) The search for ν_μ to ν_e oscillations at MiniBooNE

Andrew Bazarko – Princeton University

9 October 2003

WIN03 – Weak Interactions and Neutrinos

Lake Geneva, Wisconsin



MiniBooNE status snapshot

MiniBooNE has been running for 1 year at Fermilab

acquired 15% of goal 10^{21} protons on target

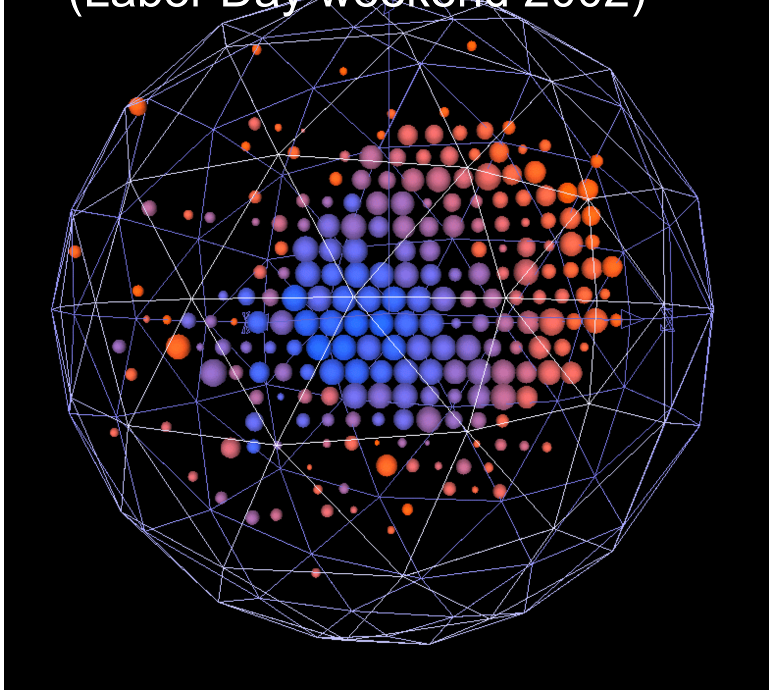
At the moment (Sept – mid Nov) accelerator is shutdown

important accelerator improvements are underway

MiniBooNE's first event:

beam-induced muon

(Labor Day weekend 2002)

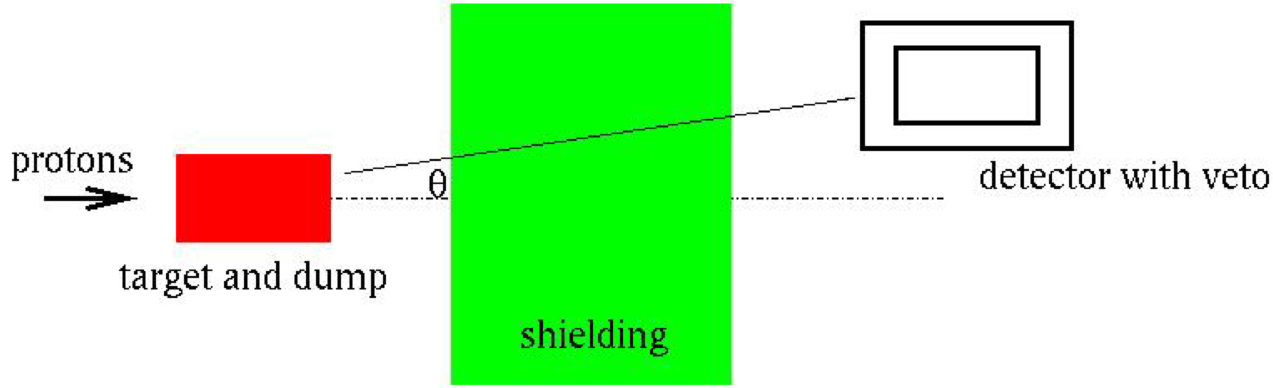


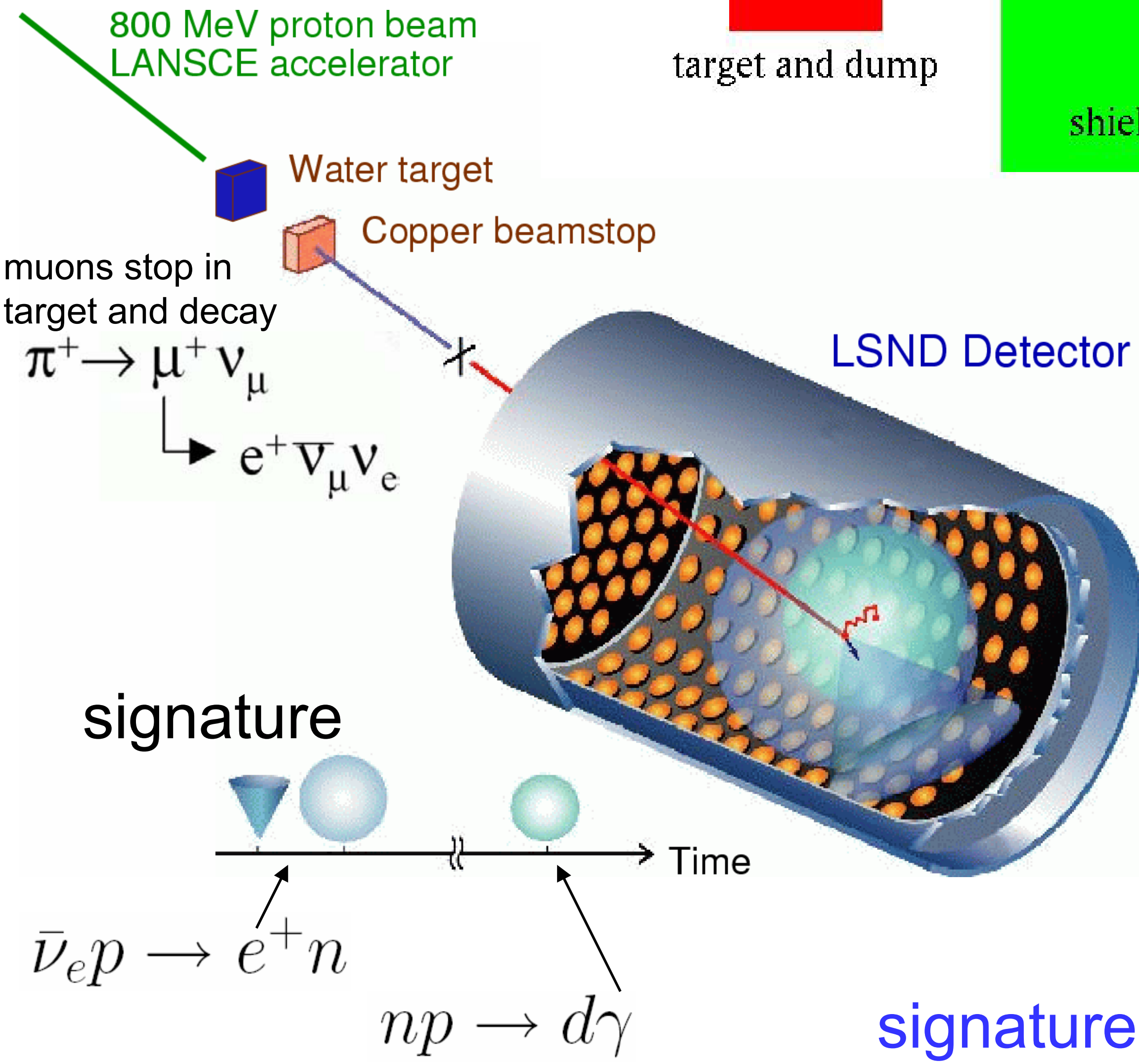
Outline

- Overview of the experiment
  - (preview of tomorrow's tour)
- First neutrino events and analysis

- Outlook

LSND (1993-1998)





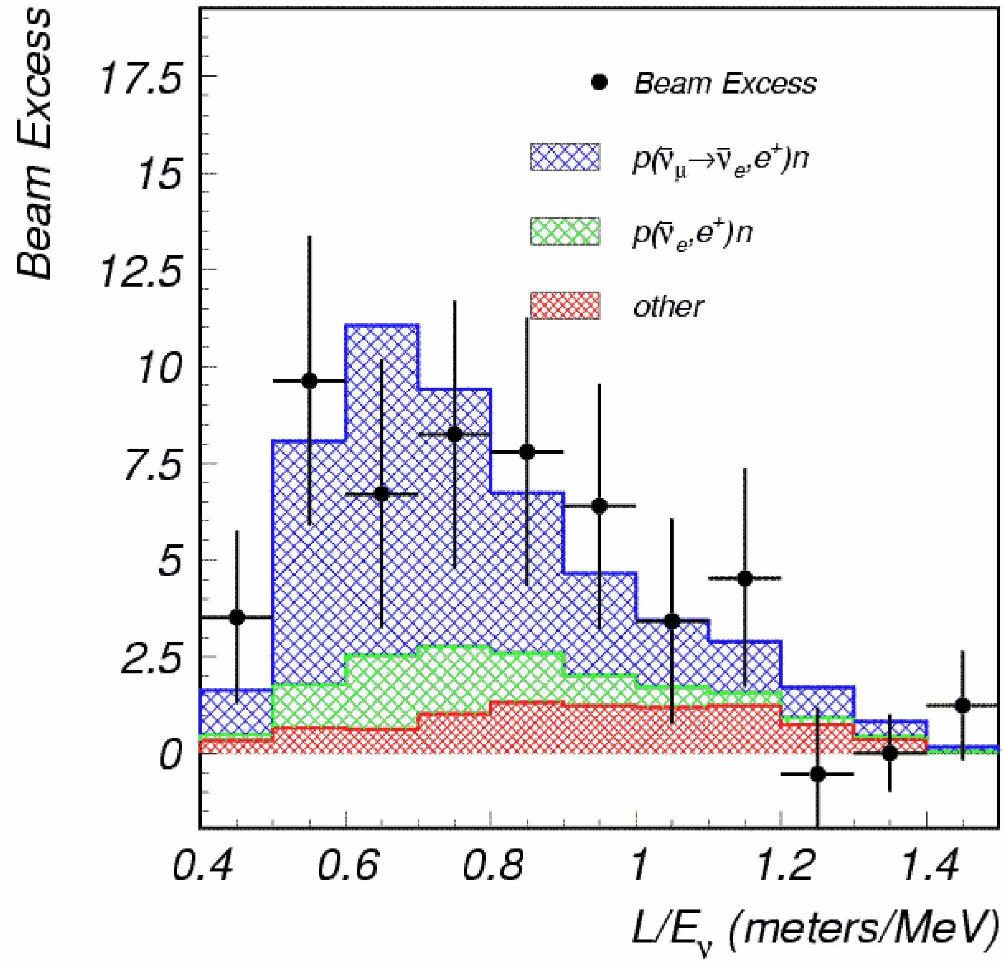
Baseline 30 m

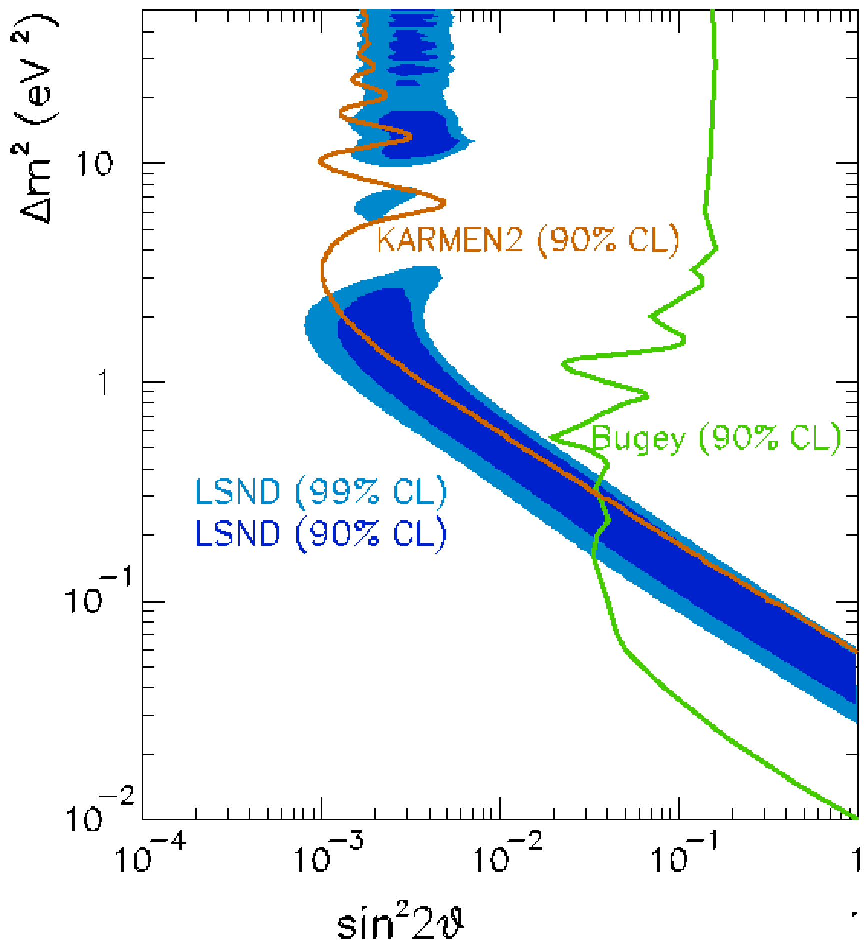
Energy range
20-55 MeV

L/E ~ 1 m/MeV

signature is *e* and γ sequence

LSND: Evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$





87.9±22.4±6.0 events

$\Delta m^2 \sim 0.2\text{-}10\ \mathrm{eV}^2$

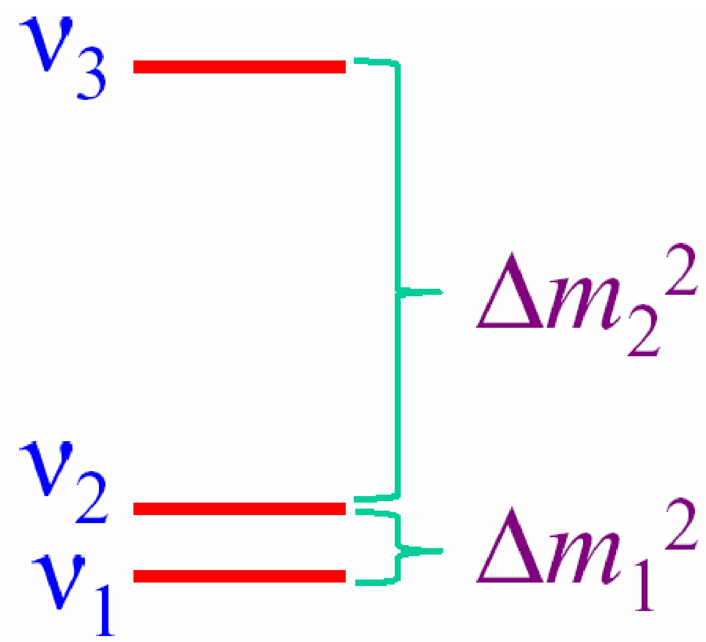
(Bugey is $\bar{\nu}_e$ disappearance)

Too many Δm^2's?

3 light neutrino flavors

Solar neutrinos:
- $\Delta m^2 \approx 7\times10^{-5} eV^2$
- mostly $\nu_e \rightarrow \nu_{\mu,\tau}$

Atmospheric neutrinos:
- $\Delta m^2 \approx 2\times10^{-3} eV^2$
- mostly $\nu_\mu \rightarrow \nu_\tau$



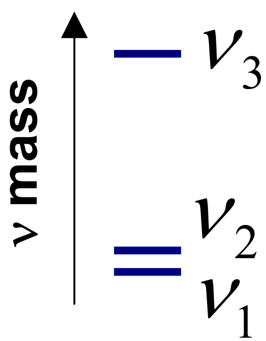
$$\Delta m_3{}^2 = \Delta m_1{}^2 + \Delta m_2{}^2$$

Where does LSND's Δm^2~0.2-10 eV^2 fit in this picture??

ν Oscillation Scenarios:

With current results from solar, atmospheric, and LSND ν−oscillation searches (3 Δm^2s), we have an interesting situation:

Only 3 active ν:

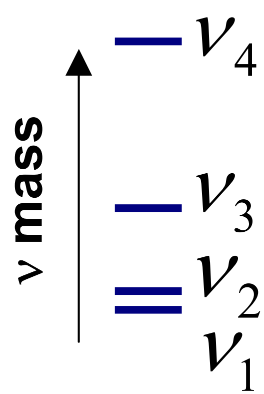


OR...

$$\text{solar}: \nu_e \to \nu_\mu$$
$$\text{atmos}: \nu_\mu \to \nu_e, \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \to \bar{\nu}_\tau \to \bar{\nu}_e$$

- not a good fit to data

3 active+1 sterile ν:

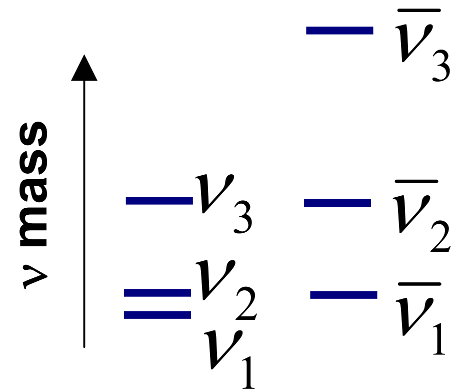


OR...

$$\text{solar}: \nu_e \to \nu_\mu, \nu_\tau$$
$$\text{atmos}: \nu_\mu \to \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \to \bar{\nu}_s \to \bar{\nu}_e$$

- possible(?)

CPT violation:



OR...

$$\text{solar}: \nu_e \to \nu_\mu$$
$$\text{atmos}: \nu_\mu \to \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \to \bar{\nu}_e$$

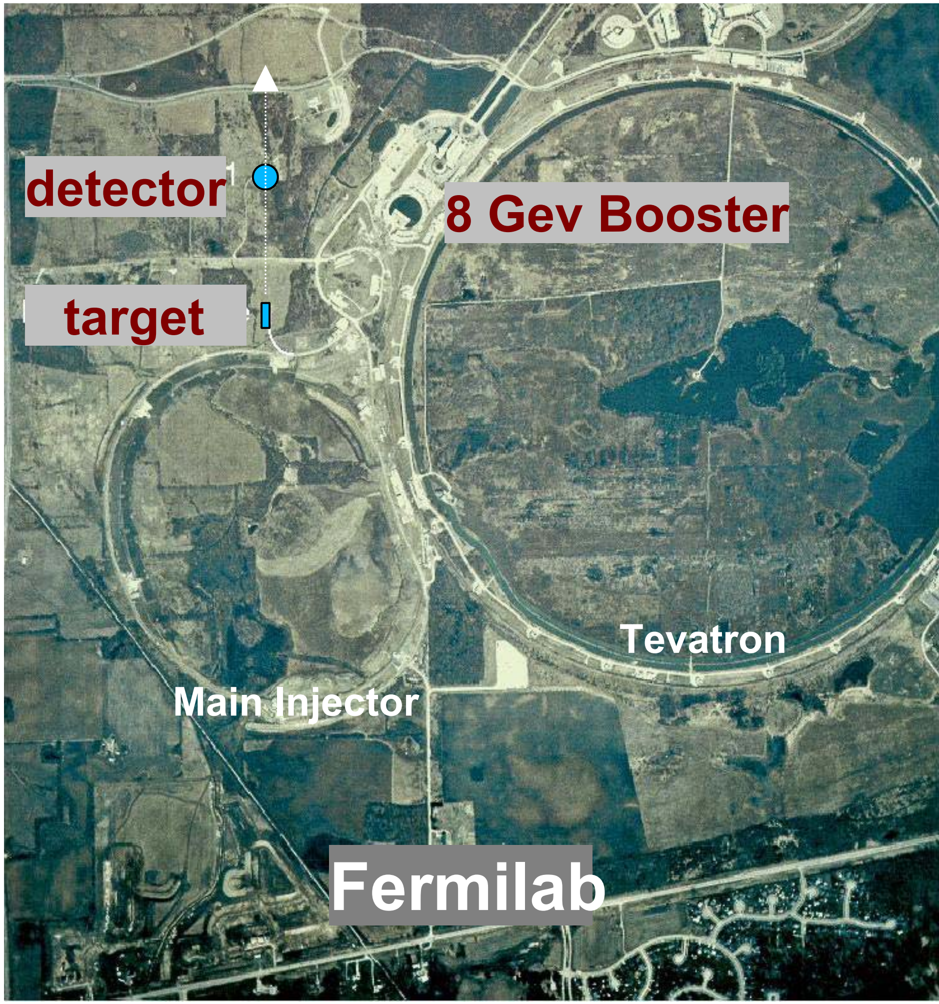
- possible(?)

Need to definitively check the LSND result.

Goal: test LSND with 5-σ sensitivity over whole allowed range

- higher statistics
- different signature
- different backgrounds
- different systematics

MiniBooNE!



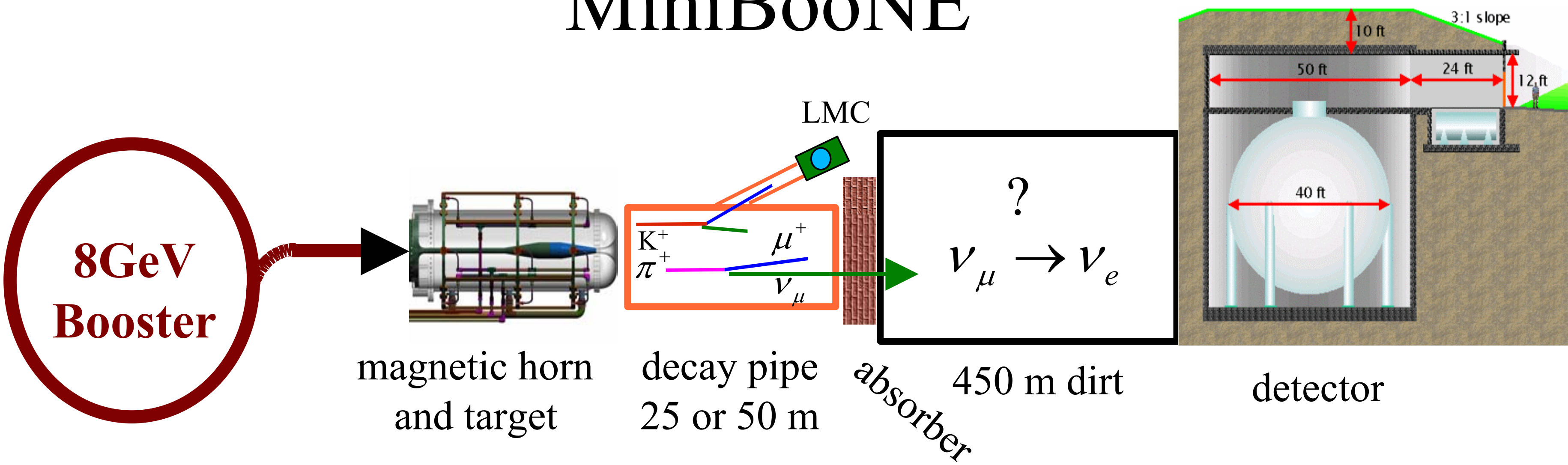
BooNE: Fermilab Booster Neutrino Experiment

First phase: "MiniBooNE"

- Single detector, $\nu_\mu \rightarrow \nu_e$ appearance
- L/E=500 m/500 MeV = 30 m/30 MeV (LSND)

Y. Liu, I. Stancu *Alabama*
S. Koutsoliotas *Bucknell*
E. Hawker, R.A. Johnson, J.L. Raaf *Cincinnati*
T. Hart, E.D. Zimmerman *Colorado*
Aguilar-Arevalo, L.Bugel, J.M. Conrad, J. Formaggio, J. Link, J. Monroe, D. Schmitz, M.H. Shaevitz, M. Sorel, G.P. Zeller *Columbia*
D. Smith *Embry Riddle*
L.Bartoszek, C. Bhat, S J. Brice, B.C. Brown, D.A. Finley, B.T. Fleming, R. Ford, F.G.Garcia, P. Kasper, T. Kobilarcik, I. Kourbanis, A. Malensek, W. Marsh, P. Martin, F. Mills, C. Moore, P. J. Nienaber, E. Prebys, A.D. Russell, P. Spentzouris, R. Stefanski, T. Williams *Fermilab*
D. C. Cox, A. Green, H.-O. Meyer, R. Tayloe *Indiana*
G.T. Garvey, C. Green, W.C. Louis, G.McGregor, S.McKenney, G.B. Mills, V. Sandberg, B. Sapp, R. Schirato, R. Van de Water, D.H. White *Los Alamos*
R. Imlay, W. Metcalf, M. Sung, M.O. Wascko *Louisiana State*
J. Cao, Y. Liu, B.P. Roe *Michigan*
A.O. Bazarko, P.D. Meyers, R.B. Patterson, F.C. Shoemaker, H.A.Tanaka *Princeton*

MiniBooNE



8-GeV protons on Be target →

π^+, K^+,…, focused by horn

decay in 50-m pipe, mostly to ν_μ

all but ν absorbed in steel and dirt

ν's interact in 40-ft tank of mineral oil

charged particles produce light

detected by phototube array

Look for electrons produced by mostly-ν_μ beam

The Booster

8 GeV proton accelerator supplies beam to all Fermilab experiments

It must now run at record intensity

MiniBooNE runs simultaneously with the collider program; goals:

Booster → MiniBooNE: 5×10^{20} p.o.t per year (1×10^{21} total)

Booster → Main Injector →
- antiproton source
- TeVatron
- NuMI
- 120 GeV fixed target

MiniBooNE: negligible impact on collider; improvements to Booster good for NuMI

Booster performance

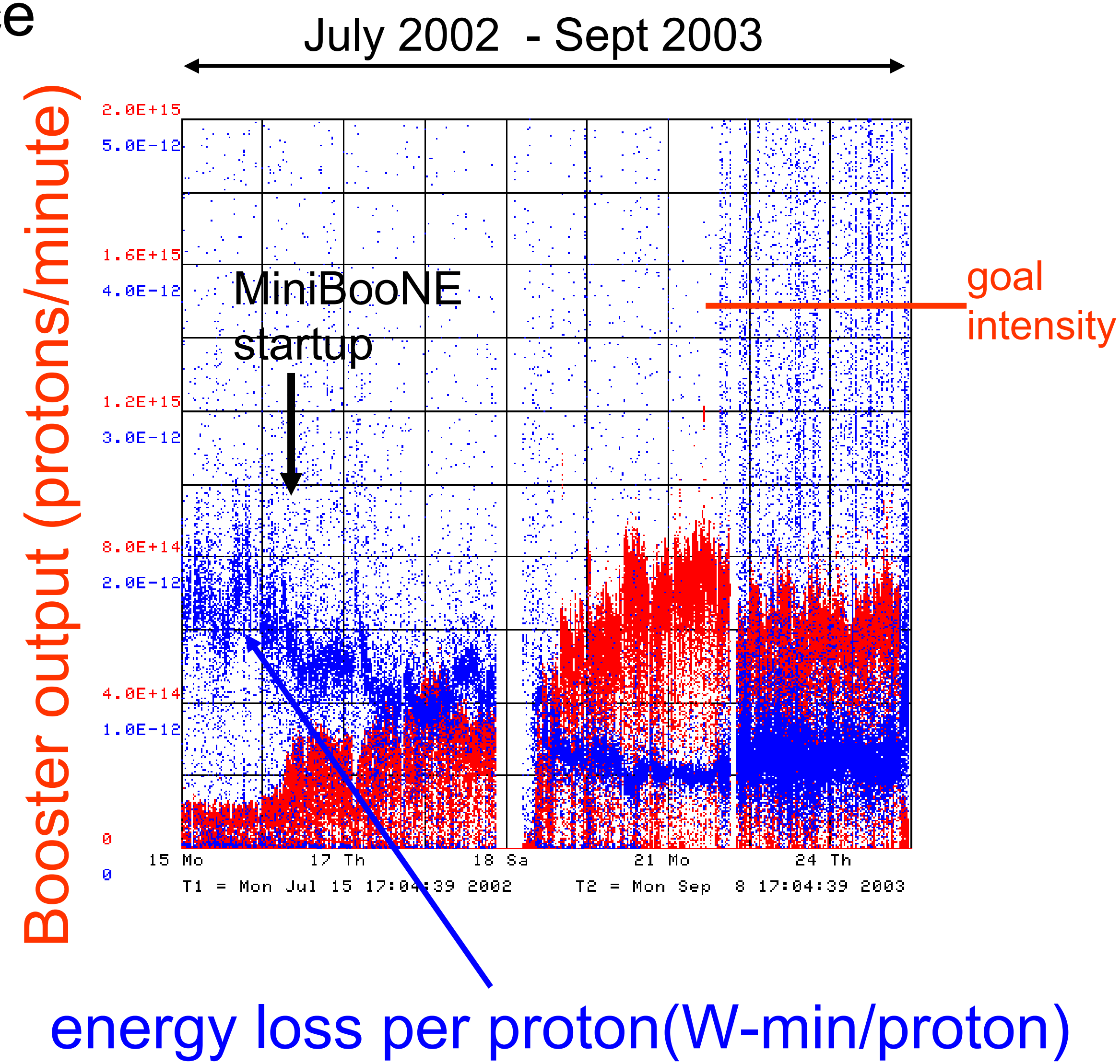
We are pushing the Booster hard

Must limit radiation damage and activation of Booster components:
  increase protons
  but decrease beam loss

~steady improvements
  careful tuning
  understanding optics

need factor of 2-3 to reach goal 10^{21} p.o.t. by early 2005

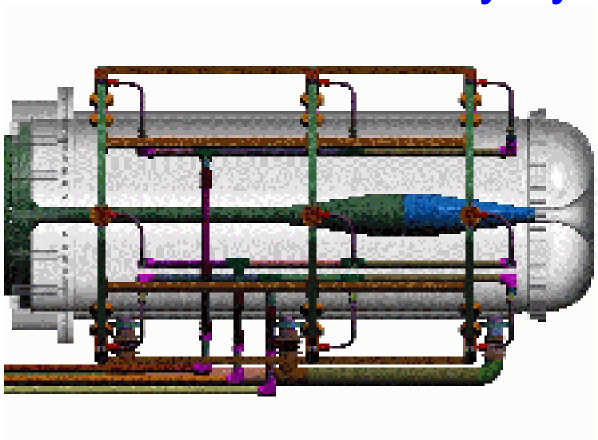
further improvements coming
  collimator project (now)
  large-aperture RF cavities



Target and magnetic horn

Increases neutrino intensity by 7x

protons



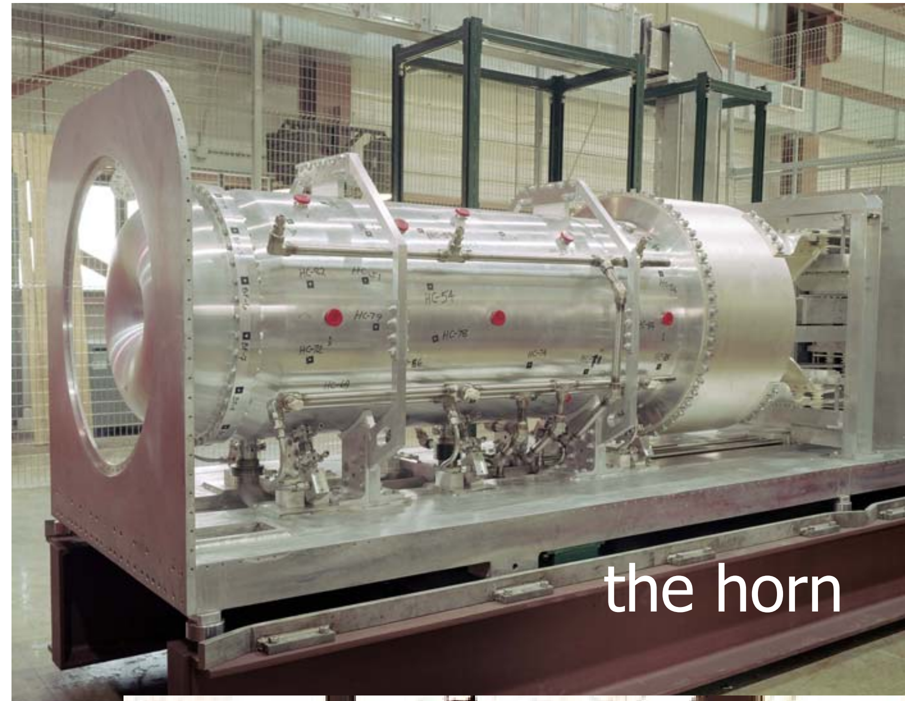
170 kA in 140 μsec pulses @ 5 Hz

Currently positive particles are being focused, selecting neutrinos $\pi^+ \to \mu^+ \nu_\mu$

the horn current can be reversed to select antineutrinos $\pi^- \to \mu^- \bar{\nu}_\mu$

Prior to run, tested to
10M pulses
has performed flawlessly:
40M pulses in situ

World's longest-lived horn



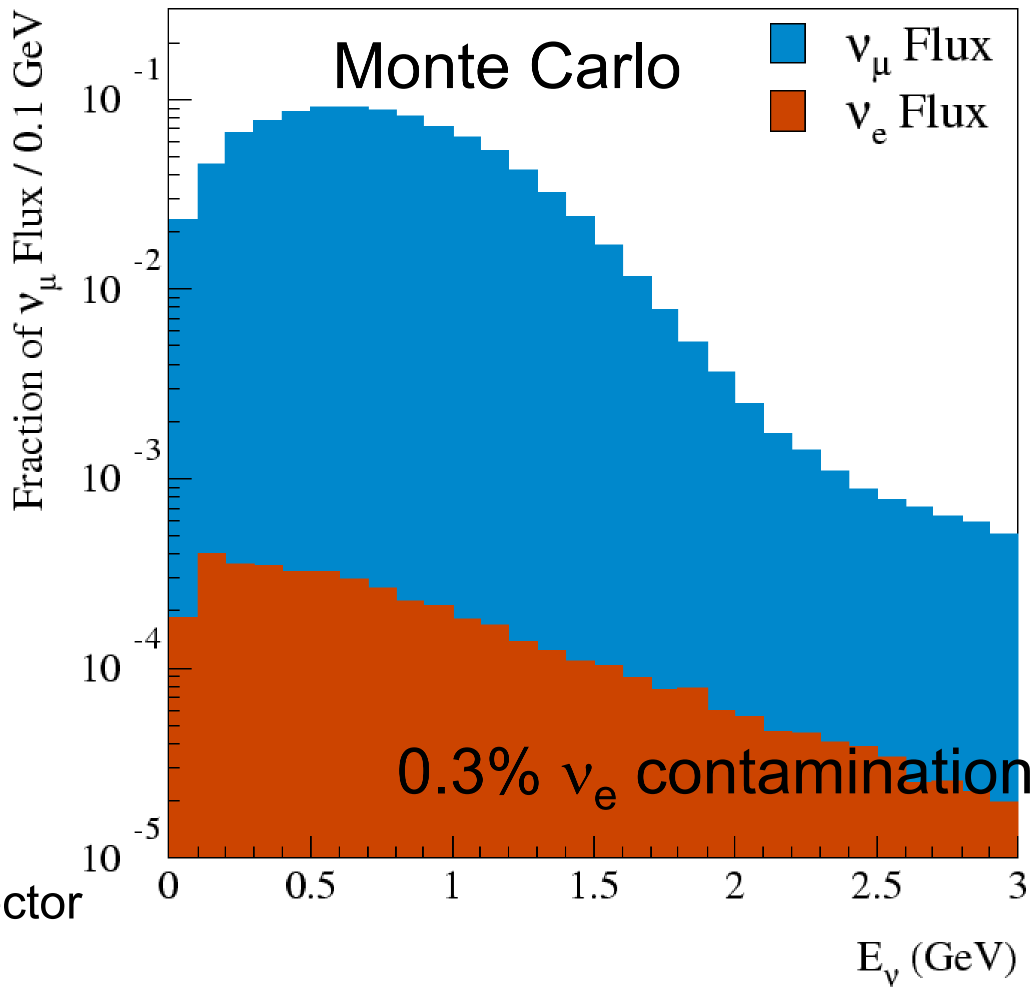
Intrinsic ν_e in the beam

$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

$K^+ \rightarrow \pi^0 e^+ \nu_e$

$K_L \rightarrow \pi^- e^+ \nu_e$



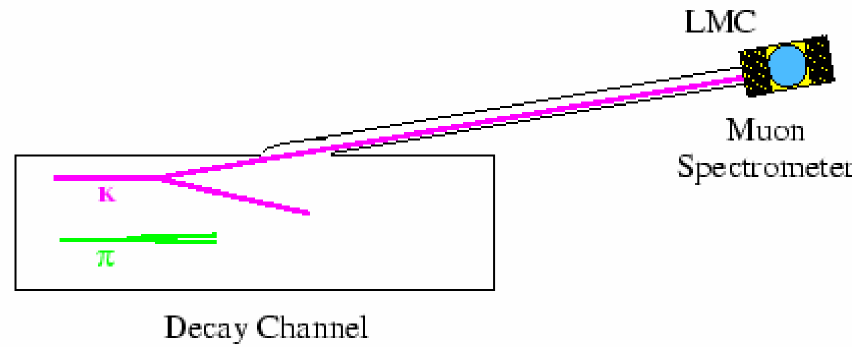
important bkgd to osc search

Tackle this background with

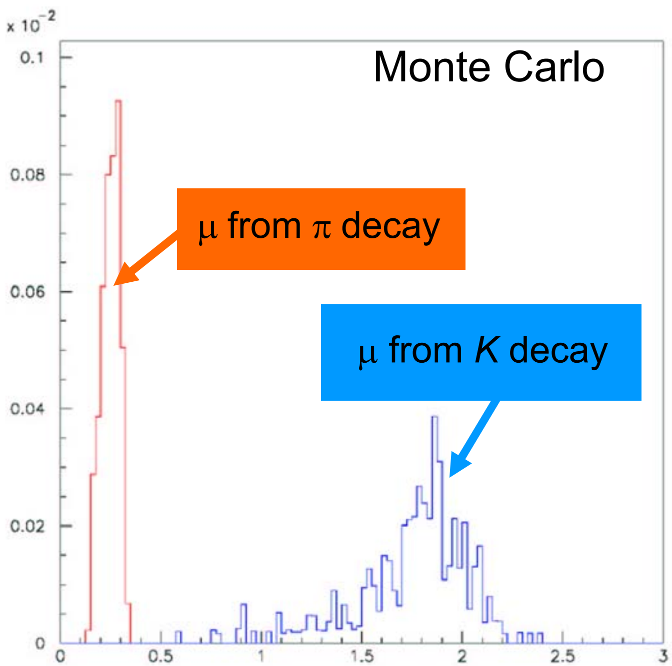
- half-million ν_μ interactions in detector
- HARP experiment (CERN)
- E910 (Brookhaven)
- "Little Muon Counter"
- 25 m / 50 m decay length option

Little Muon Counter (LMC)

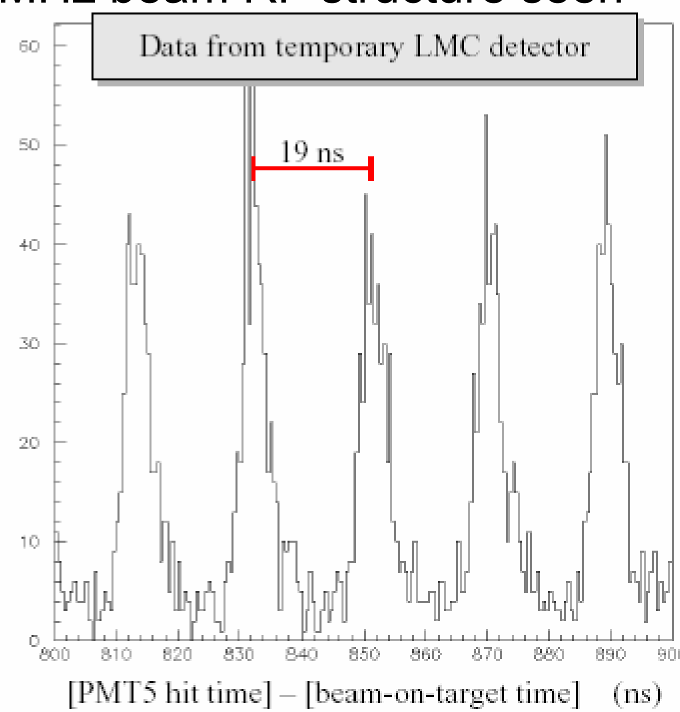
- off-axis (7°) muon spectrometer
- *K* decays produce higher-energy wide-angle muons than π decays
- clean separation of muon parentage
- scintillating fiber tracker



temporary LMC detector (scintillator paddles)
commission data acquisition
53 MHz beam RF structure seen



muon momentum at 7° (GeV)




The MiniBooNE detector

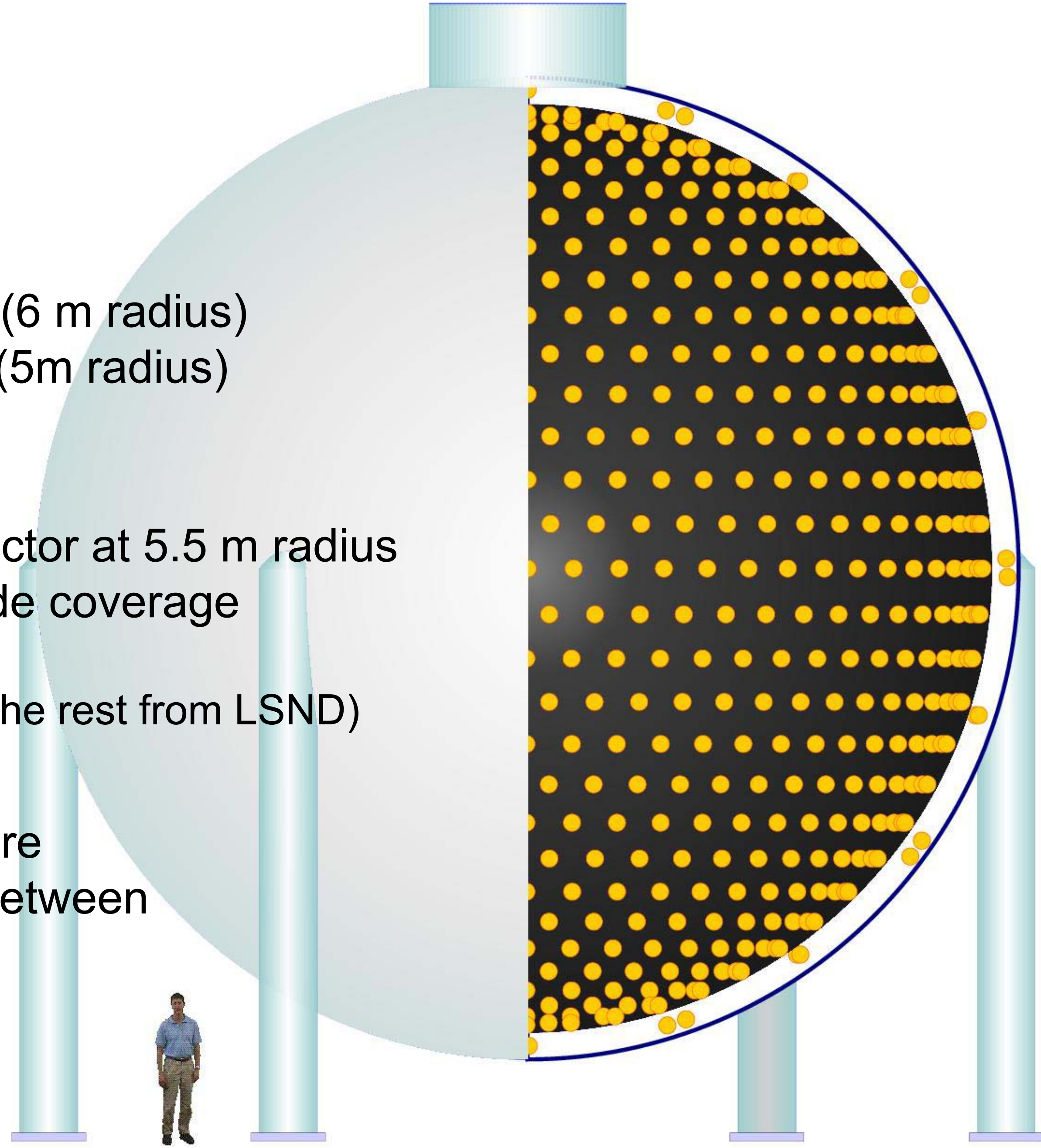
MiniBooNE detector

pure mineral oil

total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5m radius)

1280 20-cm PMTs in detector at 5.5 m radius
$\longrightarrow$ 10% photocathode coverage
240 PMTs in veto
(330 new tubes, the rest from LSND)

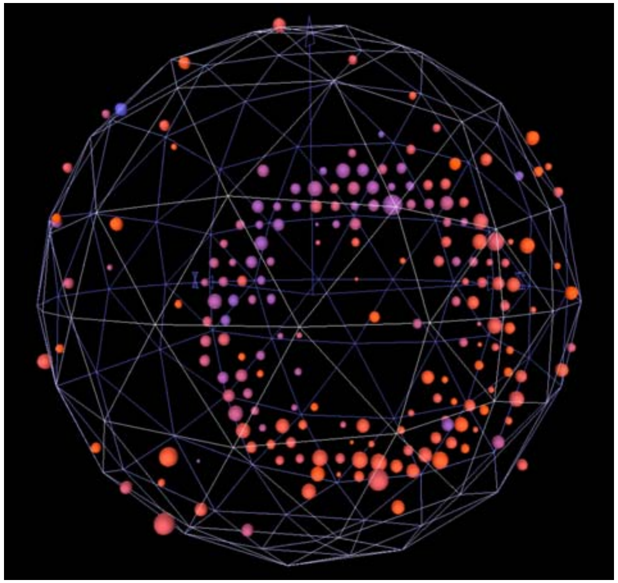
Phototube support structure
provides opaque barrier between
veto and main volumes



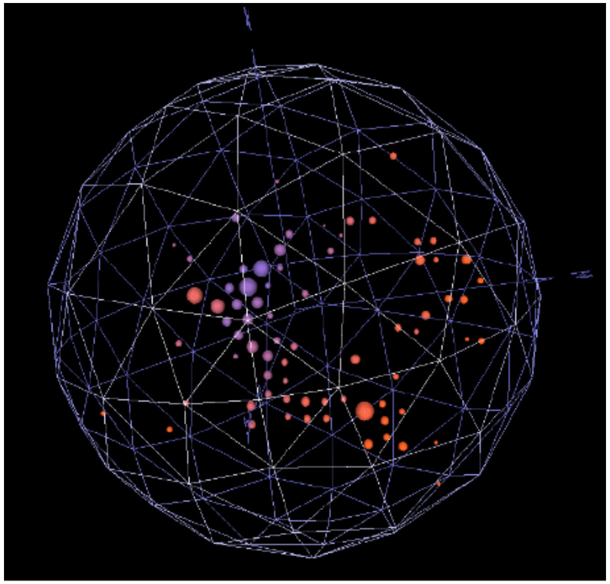
Pattern of hit tubes (with charge and time information)
allows reconstruction of track location and direction
and separation of different event types.

e.g. candidate events:

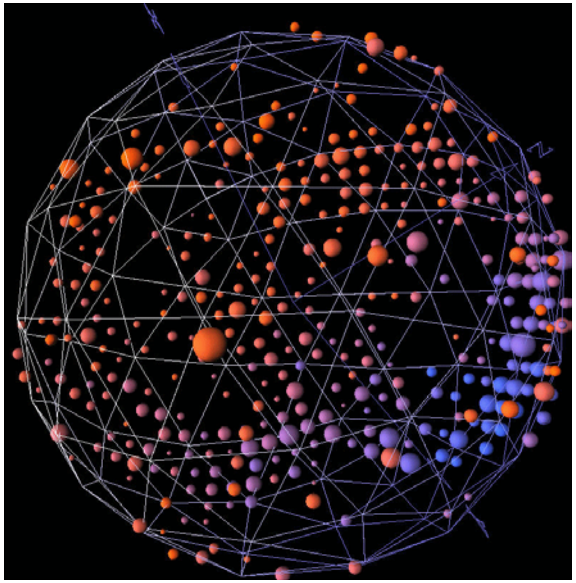
size = charge, color = time



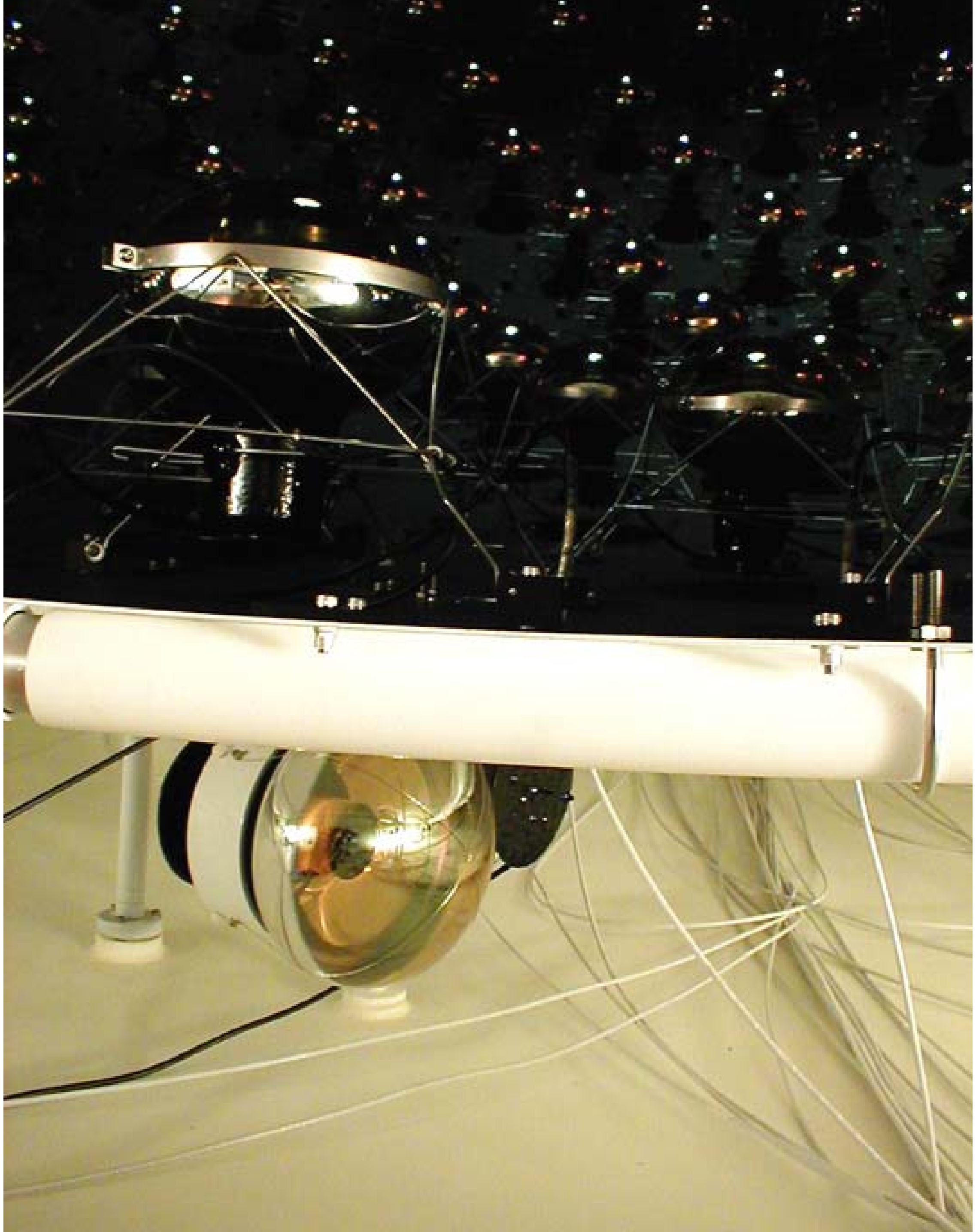
muon
from ν_μ interaction

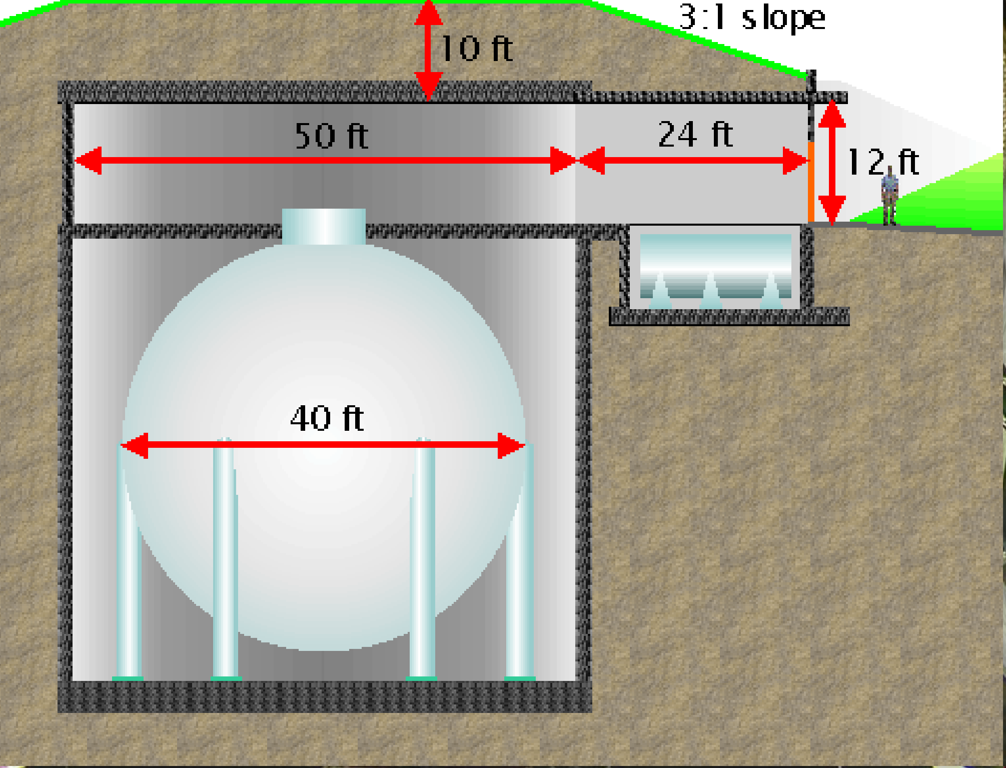


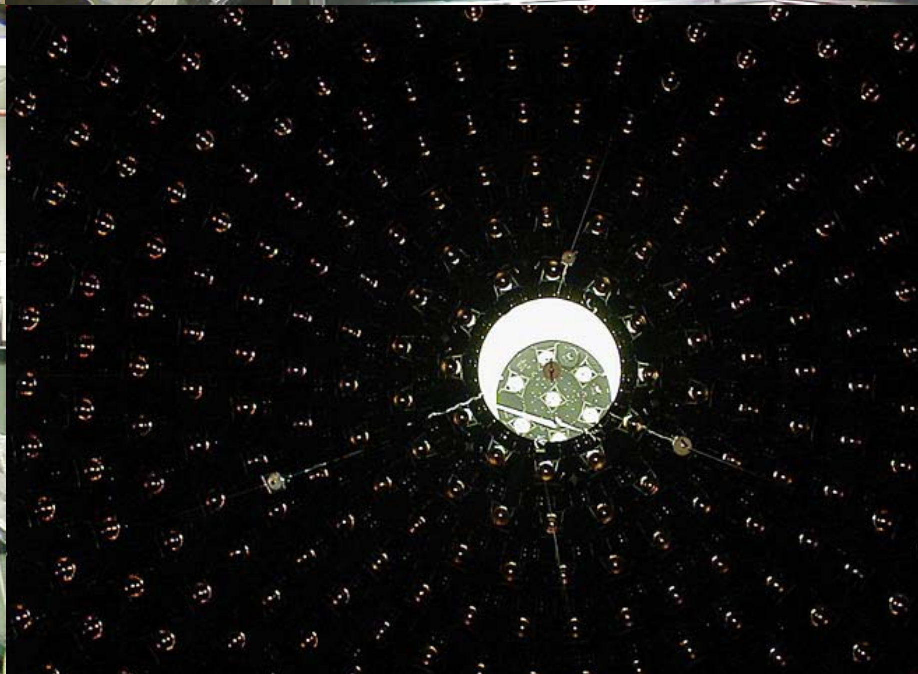
Michel electron
from stopped μ decay
after ν_μ interaction



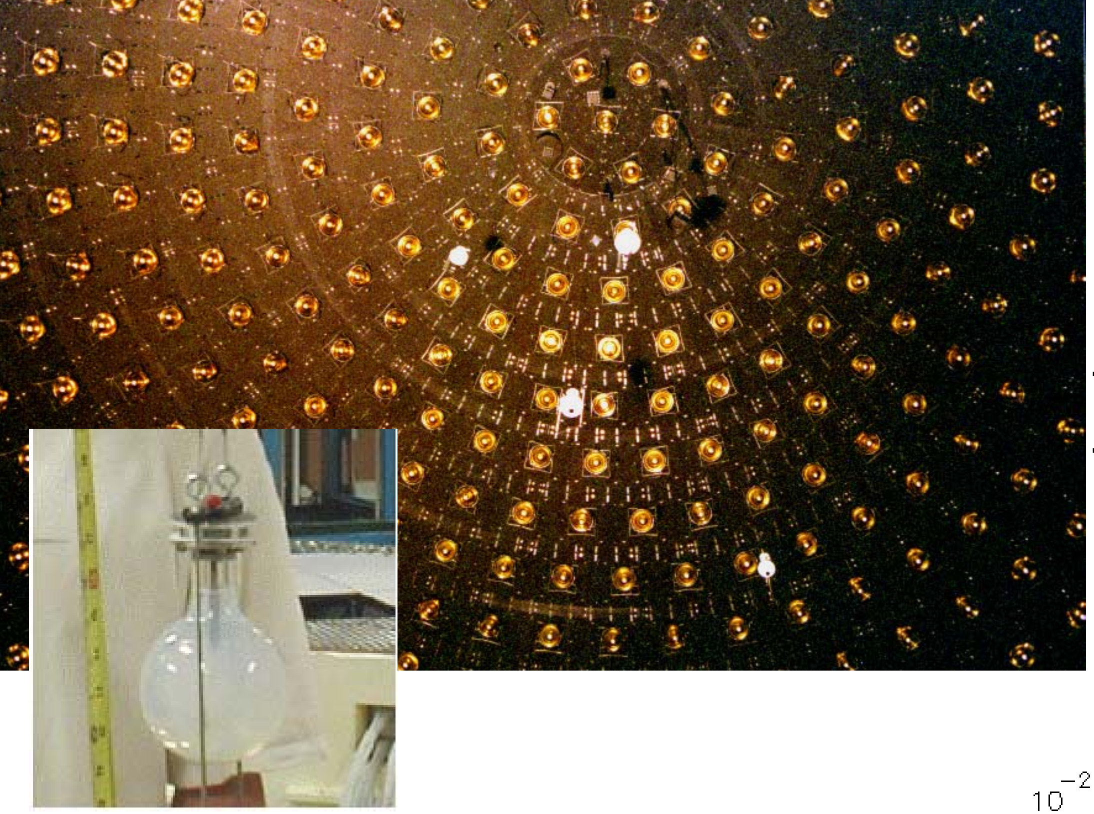
$\pi^0 \rightarrow$ two photons
from ν_μ interaction




3:1 slope
10 ft
50 ft
24 ft
12 ft
40 ft

Understanding the detector



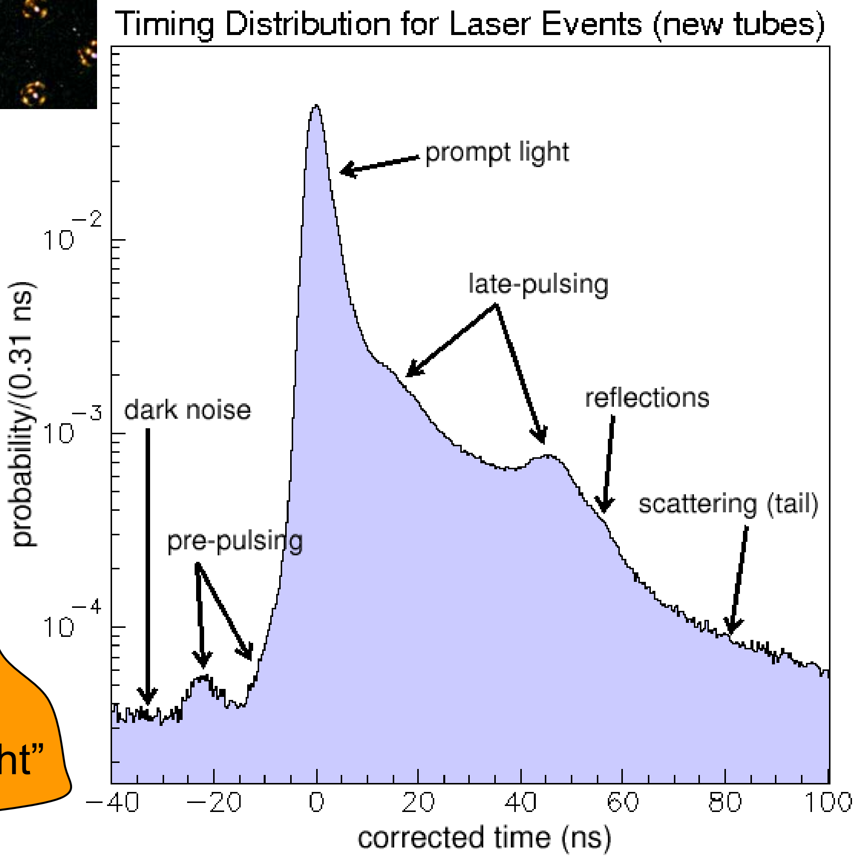
Laser flasks

four Ludox-filled flasks
fed by optical fiber from laser

measure:
PMT charge and
time response

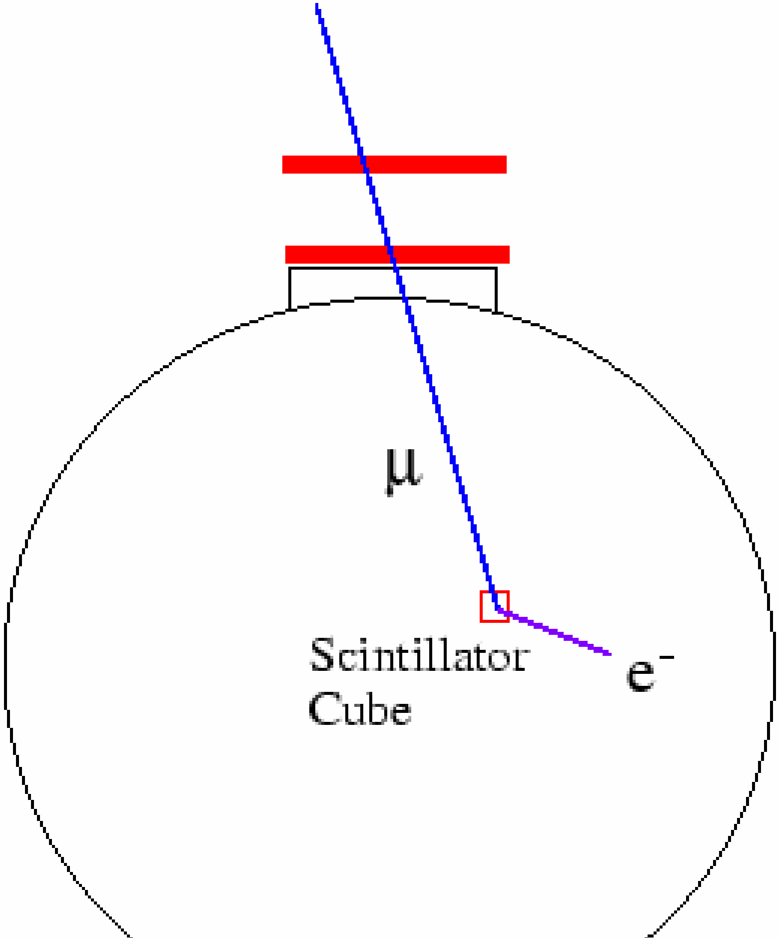
and
oil attenuation
length

397 nm laser
(no scintillation!)
modeling other
sources of "late light"

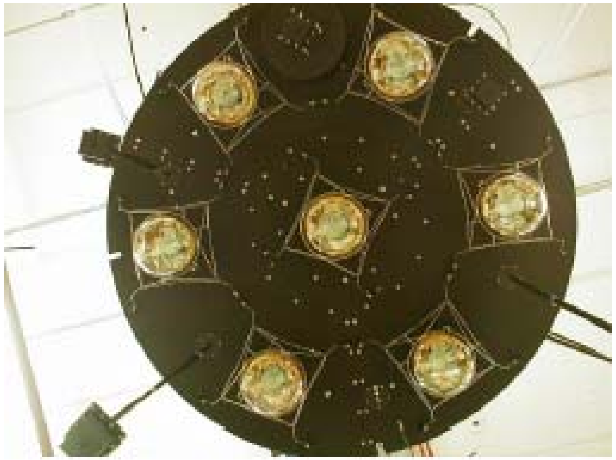


Stopping muon calibration system

Scintillator tracker above the tank

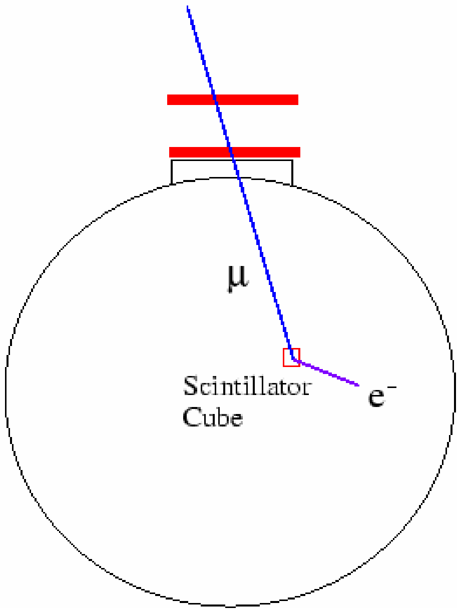


Optically isolated scintillator cubes
in tank:
six 3-inch (7.6 cm) cubes
one 4-inch cube

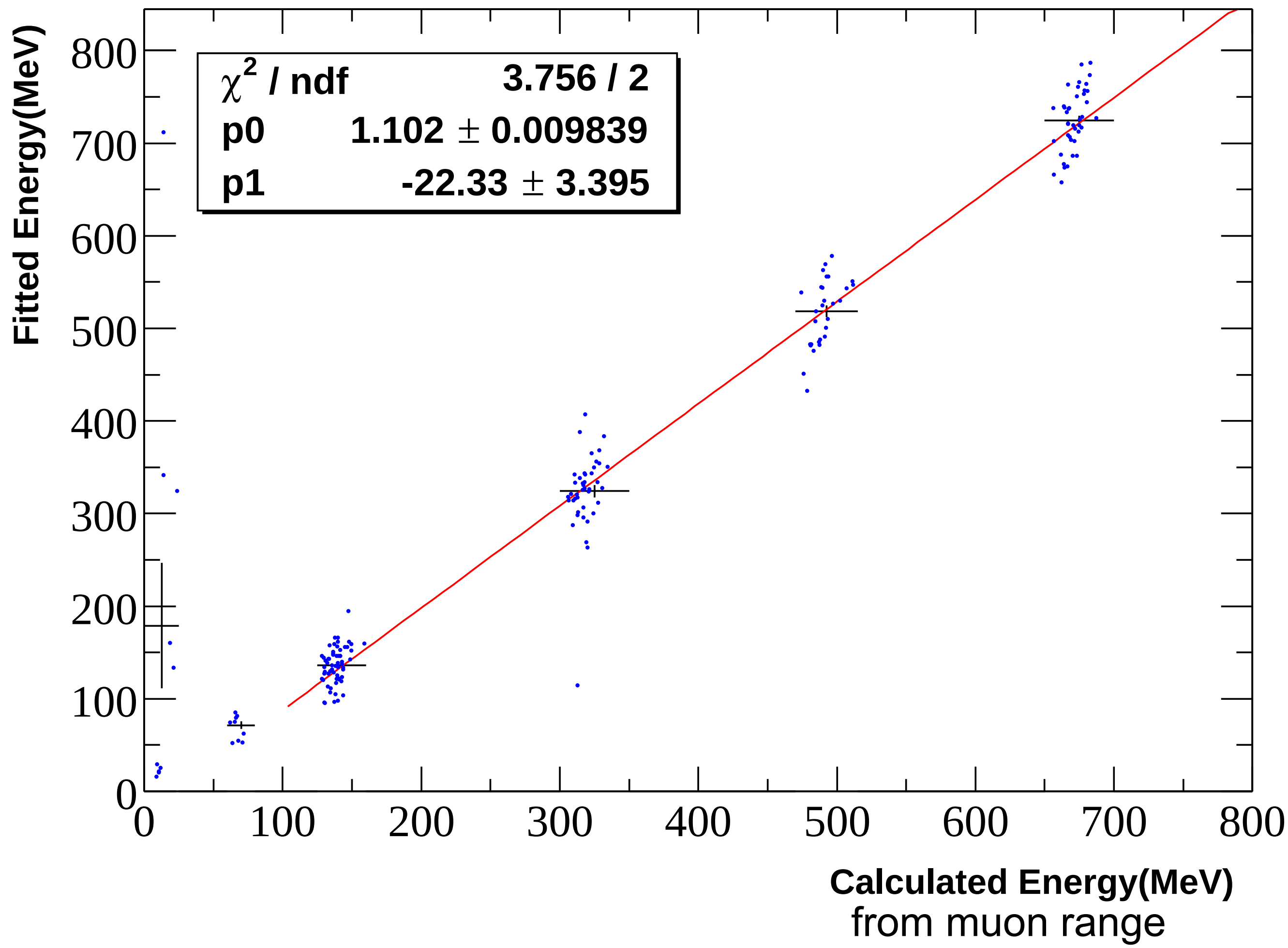


stopping muons with known path length

Compare
muon energy calculated from range
with
fitted energy (Cherenkov and scint)



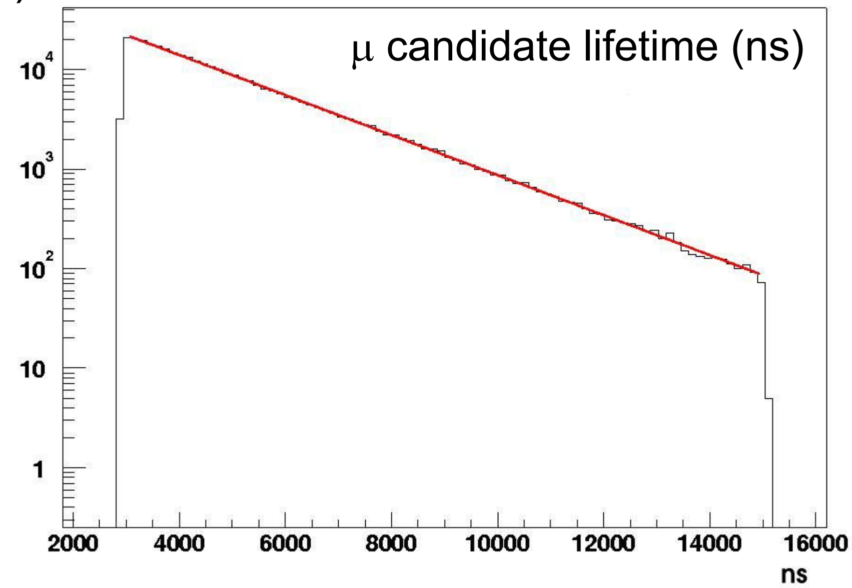
calibration sample of muons up to 700 MeV



Michel electrons

(electrons from the decay of stopped muons)

plentiful source from cosmics
and beam-induced muons



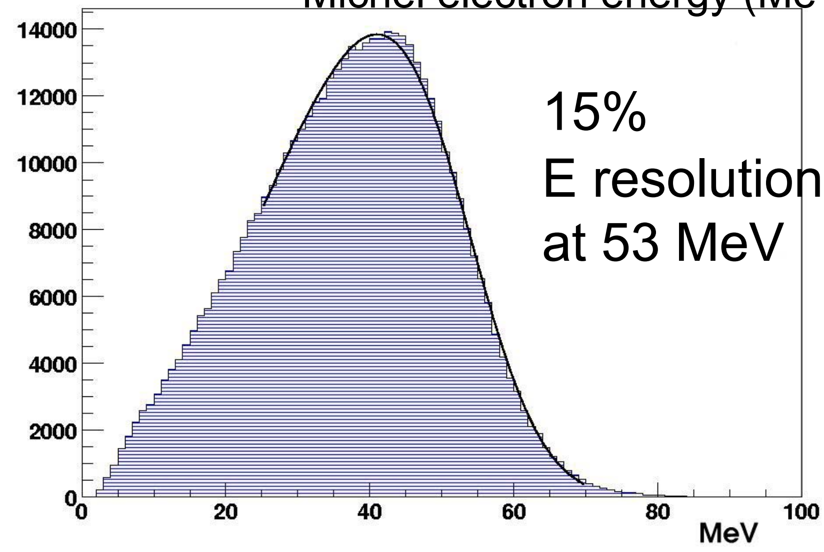
cosmic muon lifetime in oil

measured: $\tau = 2.15 \pm 0.02\ \mu s$

expected: $\tau = 2.13\ \mu s$

(8% μ^- capture)

Michel electron energy (MeV)



Energy scale and resolution
at Michel endpoint (53 MeV)

Michel electrons throughout
detector (r<500 cm)

Neutrino events

beam comes in spills @ up to 5 Hz
each spill lasts 1.6 μsec

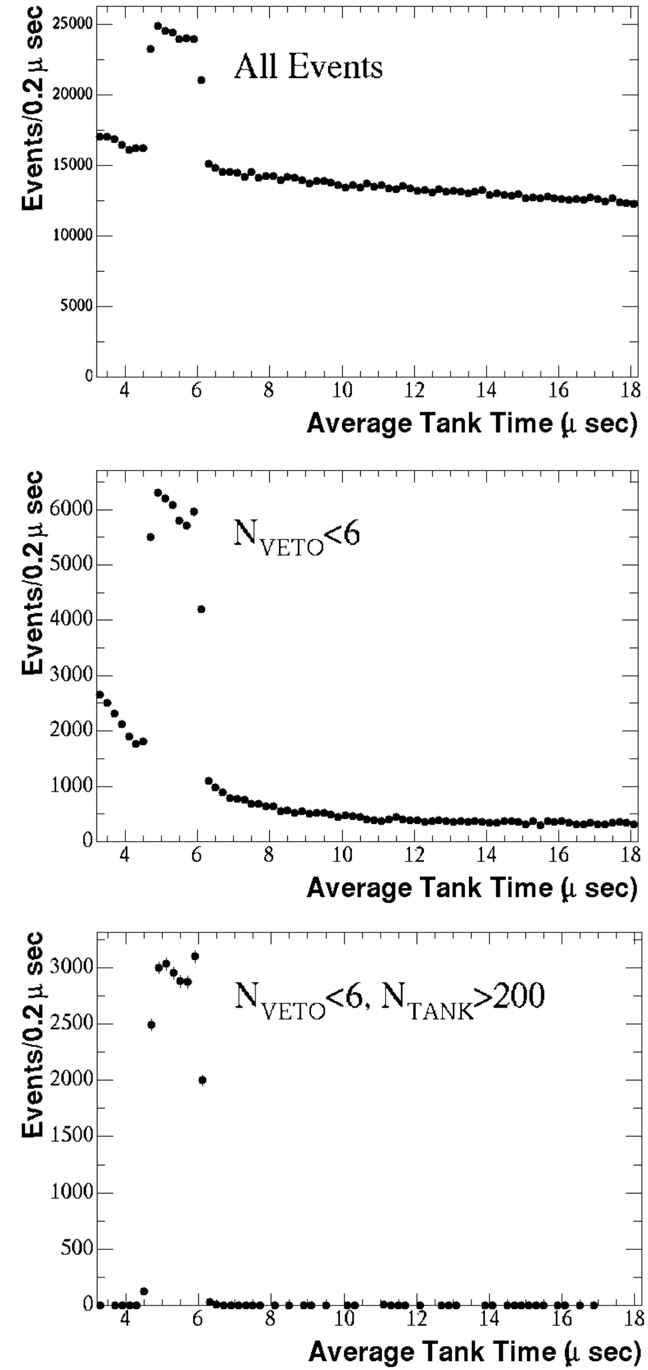
trigger on signal from Booster
read out for 19.2 μsec; beam at [4.6, 6.2] μsec

no high level analysis needed to see neutrino events

backgrounds: cosmic muons
decay electrons

simple cuts reduce non-beam backgrounds to ~10^{-3}

150k neutrino candidates in 1.6 x 10^{20} protons on target



The road to $\nu_\mu \rightarrow \nu_e$ appearance analysis

Blind ν_e appearance analysis

you can see all of the info on some events

or

some of the info on all events

but

you cannot see all of the info on all of the events

Early physics: other analyses before $\nu_\mu \rightarrow \nu_e$ appearance

interesting in their own right

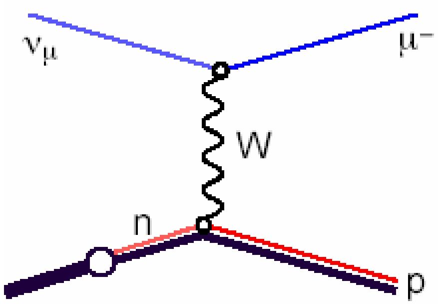
relevant to other experiments

necessary for $\nu_\mu \rightarrow \nu_e$ search

vets data-MC agreement (optical properties, etc.)
and reliability of reconstruction algorithms

progress in understanding backgrounds

CC quasi-elastic



abundance ~40%
simple topology
one muon-like ring
proton rarely above Č

~88% purity
~50% efficiency

kinematics:
$E_\mu, \theta_\mu \rightarrow E_\nu, Q^2$
relatively well-known σ:
check of flux prediction

NC π^0 production

resonant:

$$\nu + (p/n) \rightarrow \nu + \Delta$$
$$\Delta \rightarrow (p/n) + \pi$$

coherent:

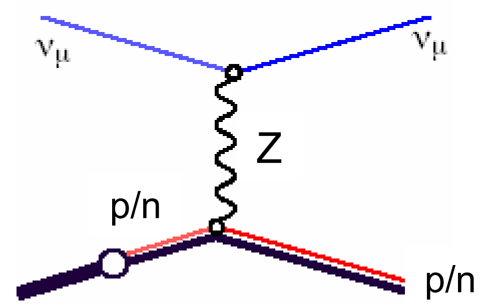
$$\nu + \mathrm{C} \rightarrow \nu + \mathrm{C} + \pi^0$$

abundance ~7%
$\pi^0 \rightarrow \gamma\,\gamma$
two rings
E1, E2 from Č intensities

reconstruct invariant
mass of two photons

background to
ν_e appearance
and
limits on sterile ν

NC elastic

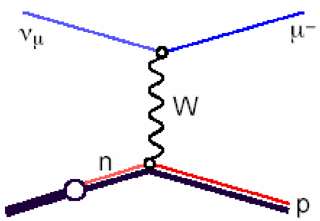


abundance ~15%
usually sub-Č
dominated by
scintillation

low Ntank (pmt hits)
high late light fraction

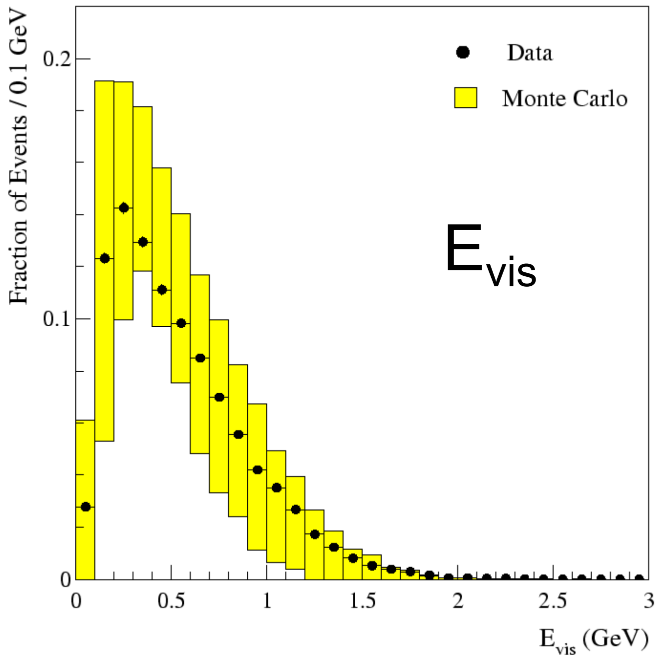
understanding of
scintillation
sensitive to nucleon
strange spin component

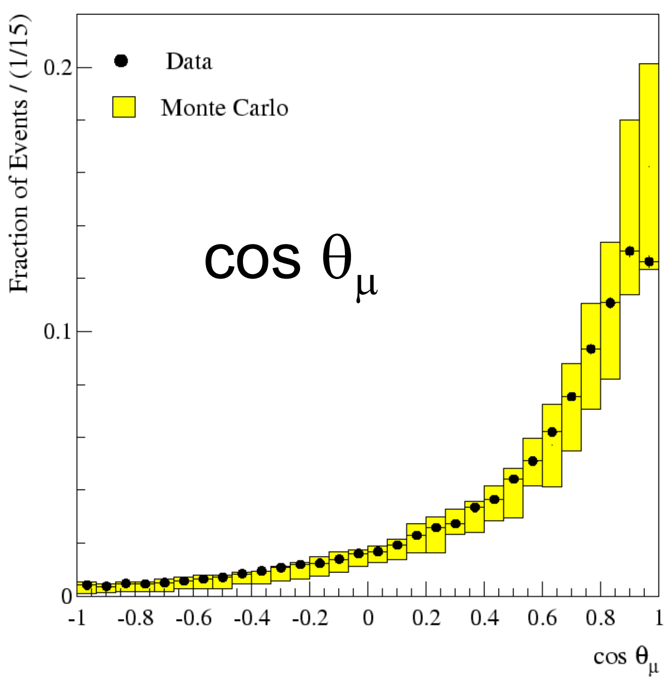
CC ν_μ quasi-elastic events



selection: topology
ring sharpness
on- vs. off-ring hits
timing
single m-like ring
decay electron

⇨ variables combined in a Fisher discriminant





yellow band: Monte Carlo with uncertainties from flux prediction

σ_{CCQE}

optical properties

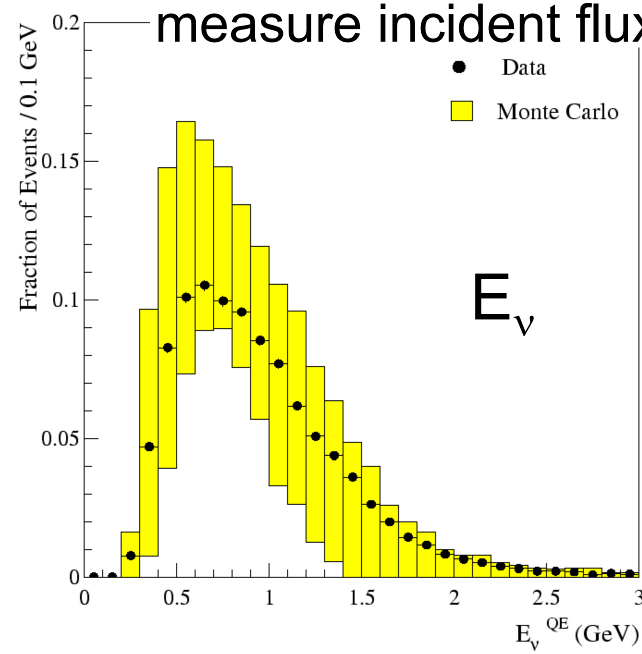
Neutrino energy

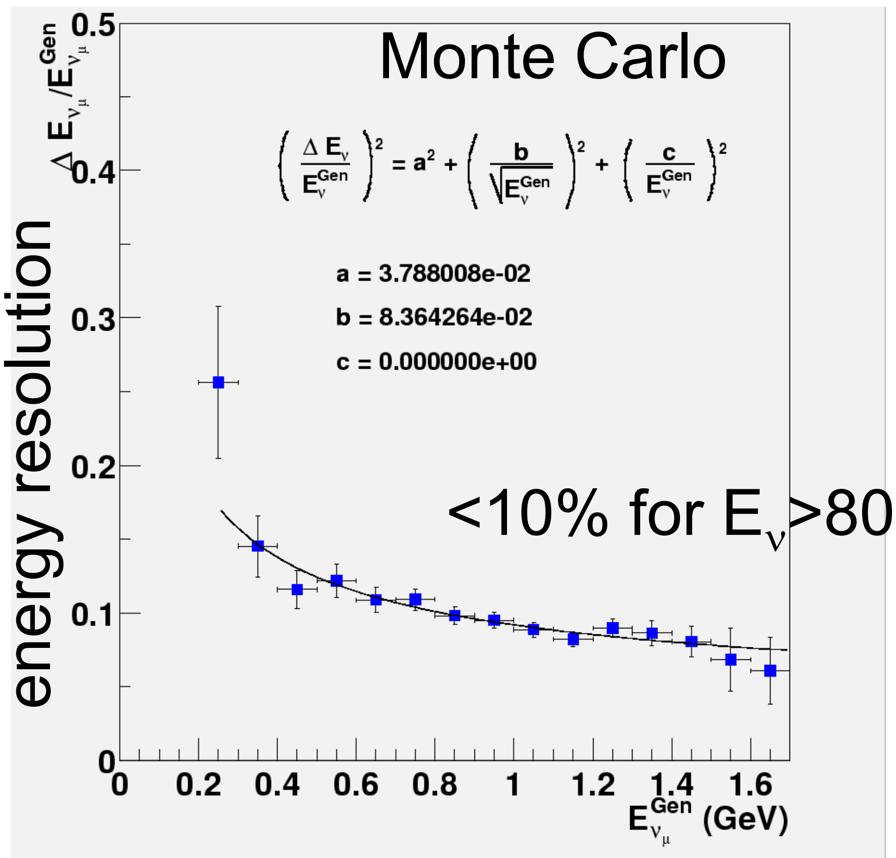
kinematic reconstruction:

assume $\nu_\mu\, n \rightarrow \mu^-\, p$

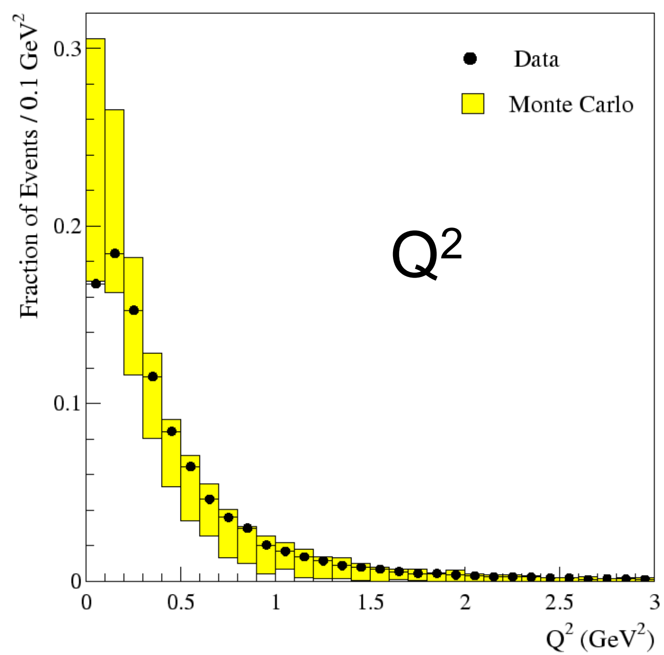
use E_μ, θ_μ to get E_ν

measure incident flux





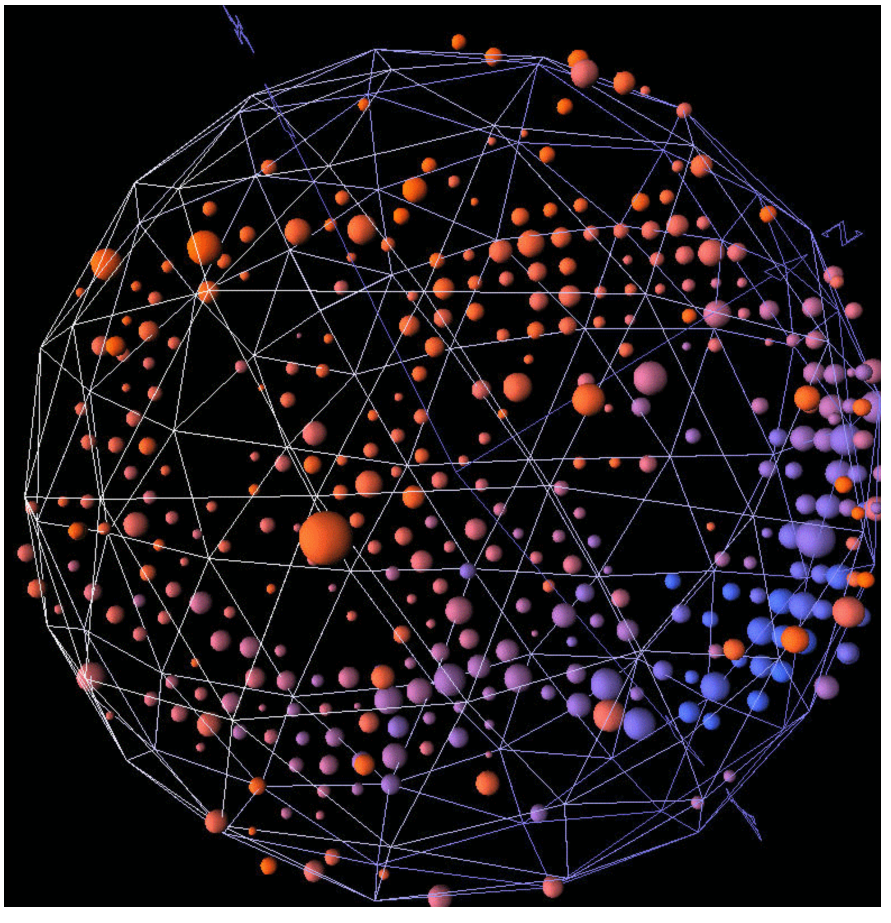
<10% for E_ν>800 MeV

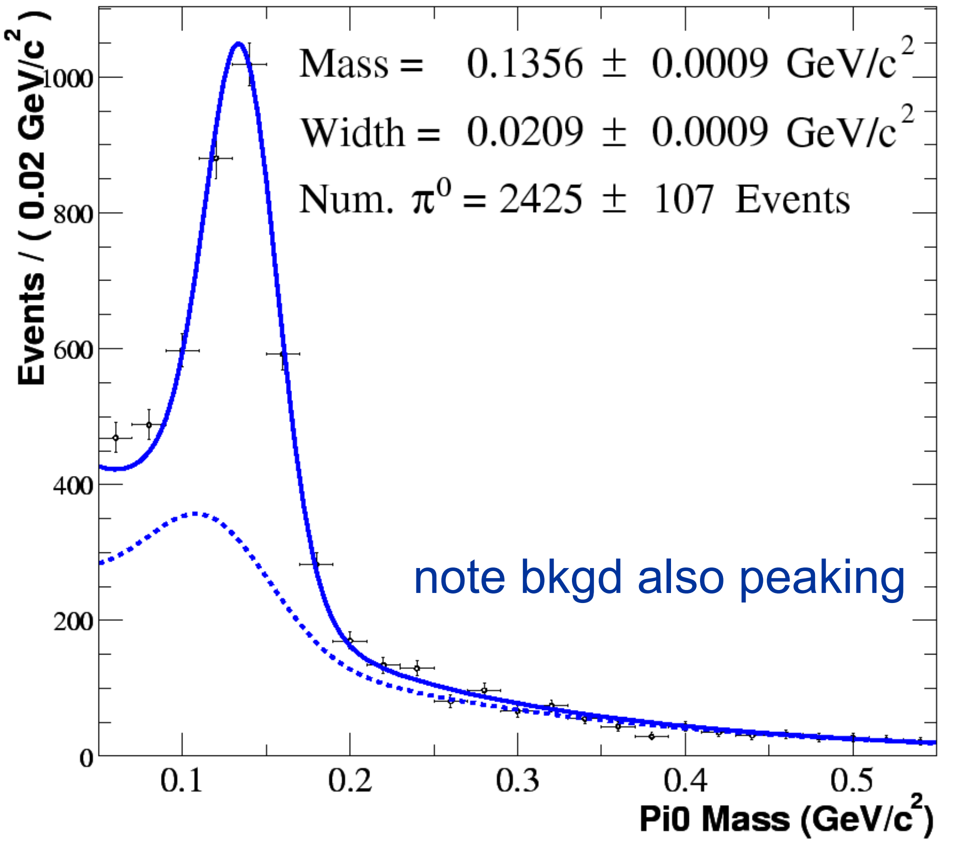


NC π^0 production

perform two ring fit on *all* events
require ring energies E_1, E_2 > 40 MeV

fit mass peak to extract signal yield
including background shape from Monte Carlo





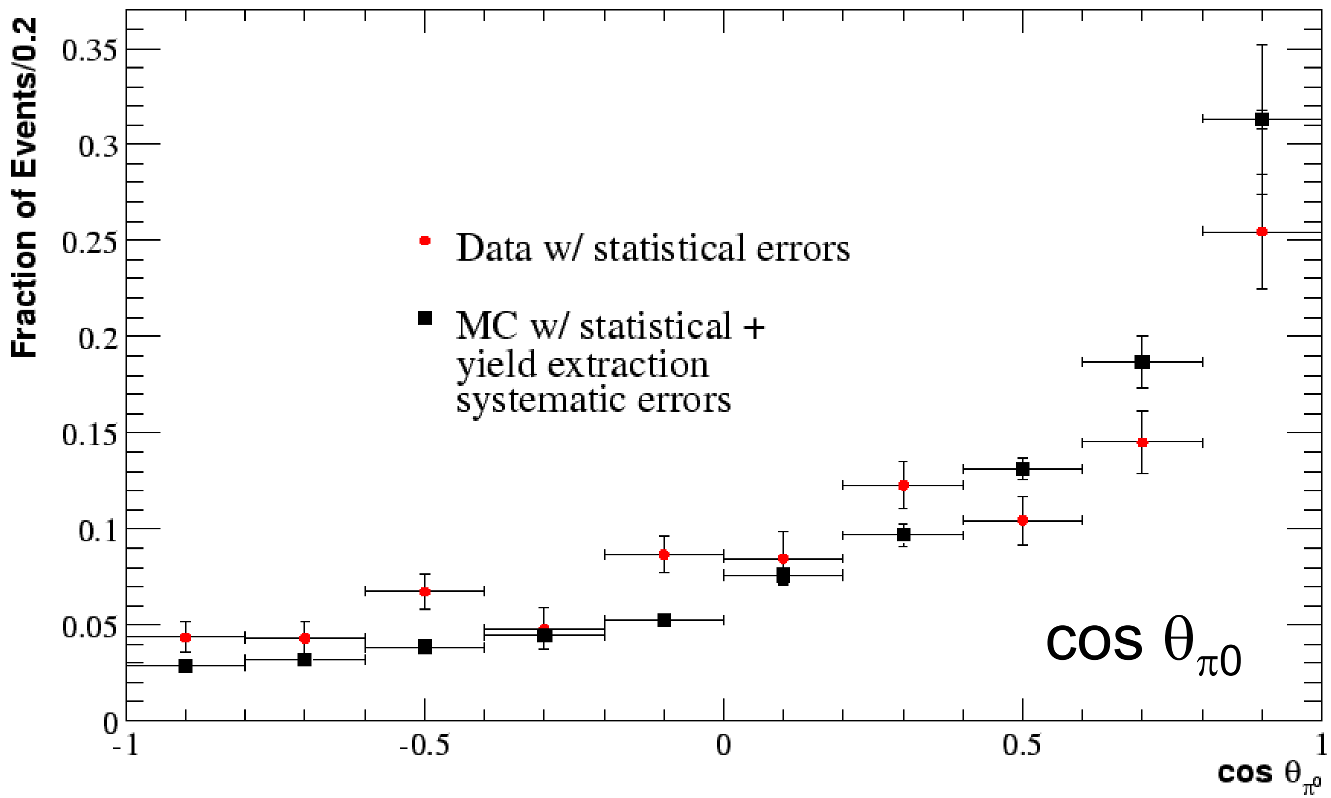
π^0 production angle

sensitive to production mechanism

coherent is highly forward peaked

MC and data are relatively normalized

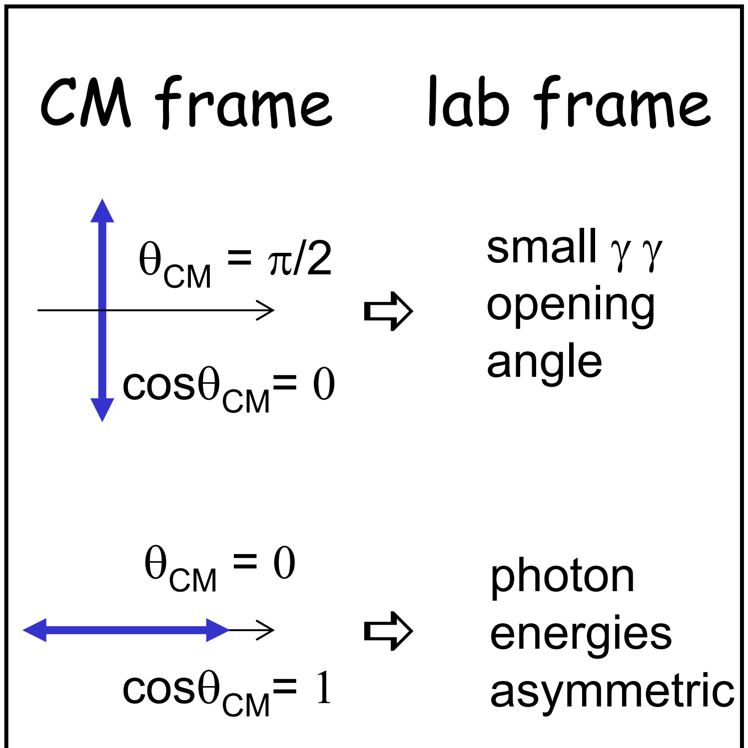
MC shape assumes Rein-Sehgal cross sections

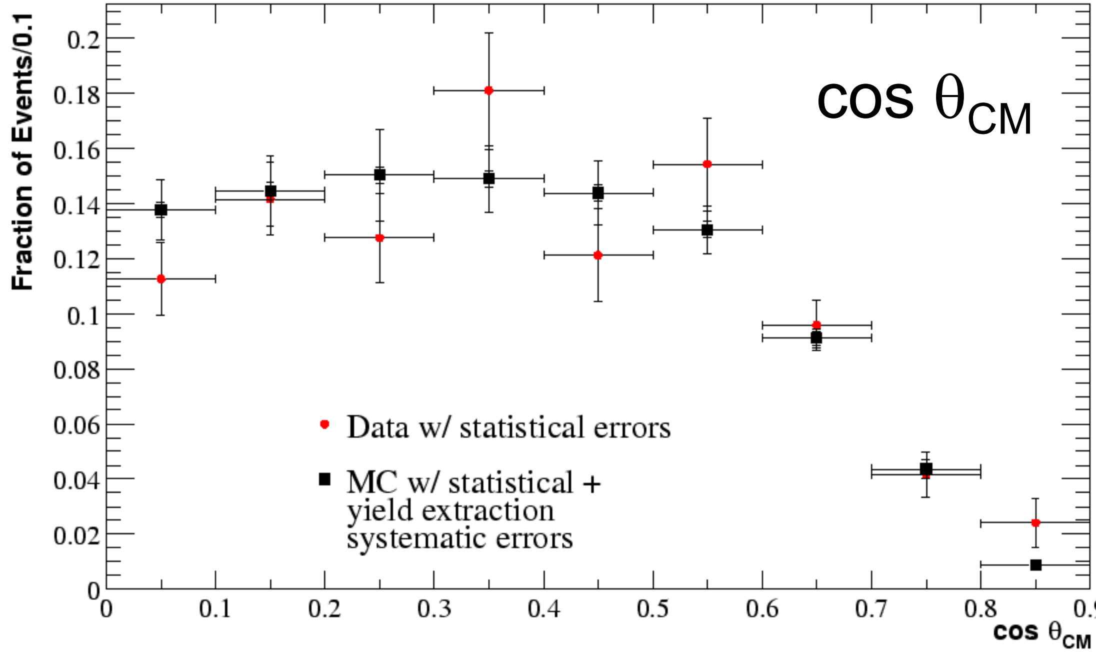


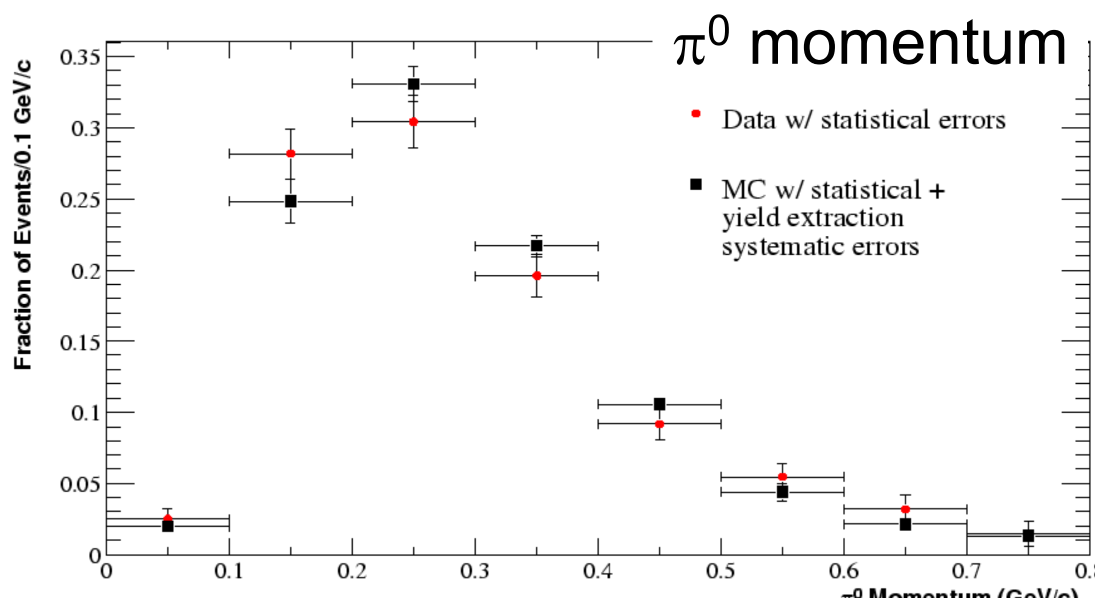
π^0 decay angle

and

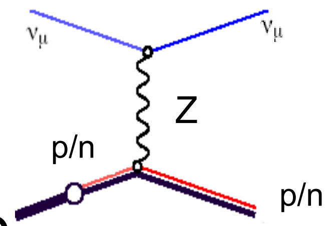
π^0 momentum

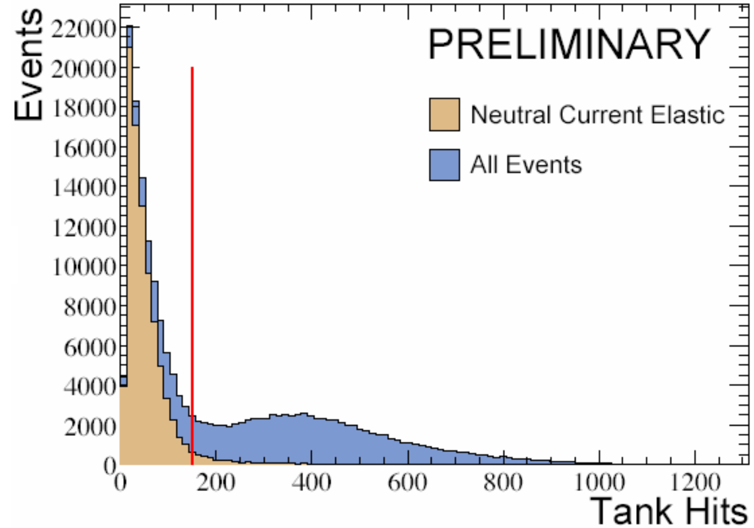






NC elastic scattering





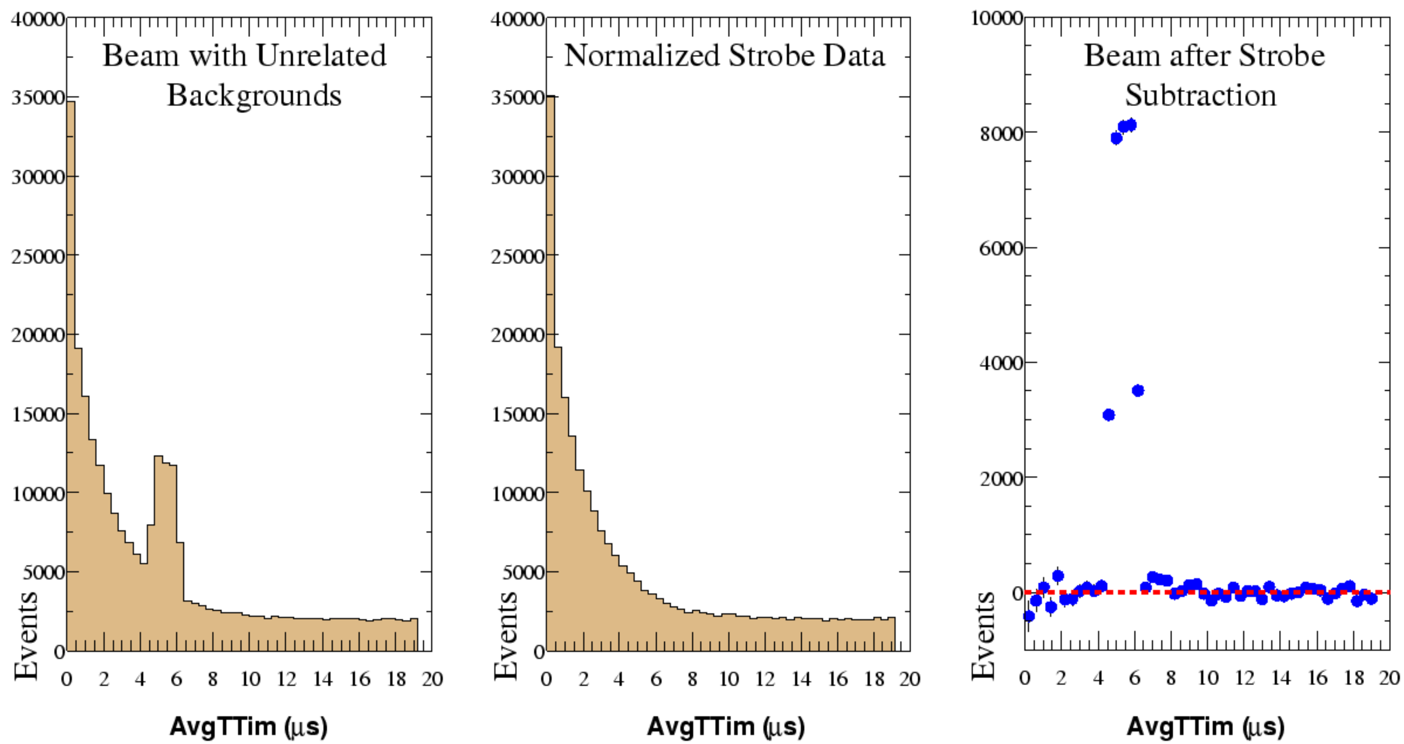
Now select $N_{TANK} < 150$

$N_{VETO} < 6$

Background subtraction

clear beam excess

use random triggers to subtract non-beam background

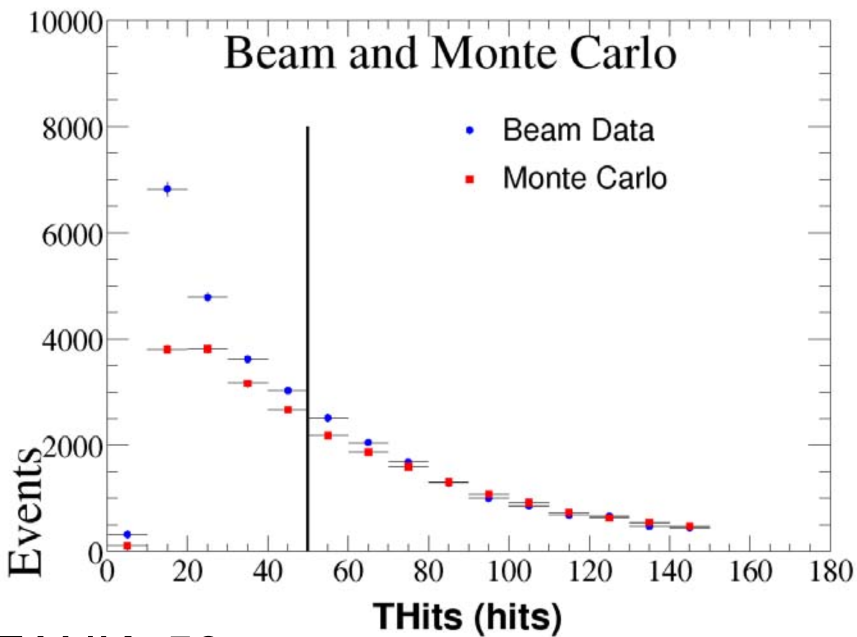


ν_μ NC elastics

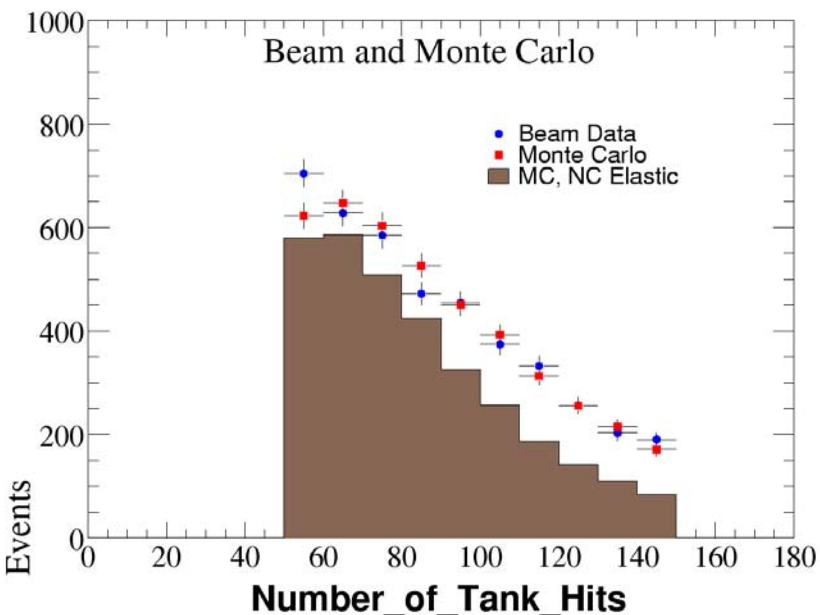
Consider N_{TANK} spectrum

MC and data shapes agree for NTANK>50

Unknown component N_{TANK}<30



data and MC relatively normalized for NTANK>50

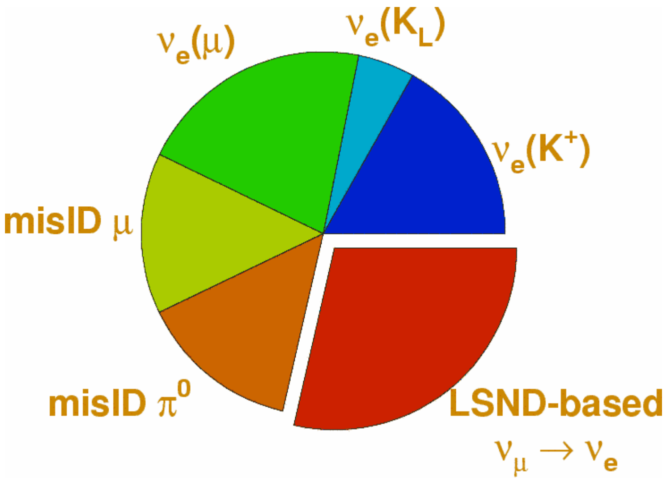


Late light selection:

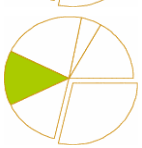
fit event vertex for N_{TANK}>50
calculate fraction of late hits
select events with significant late light

ν_e appearance sensitivity

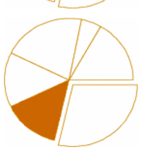
preliminary estimates,
backgrounds and signal



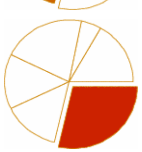
1500 intrinsic ν_e



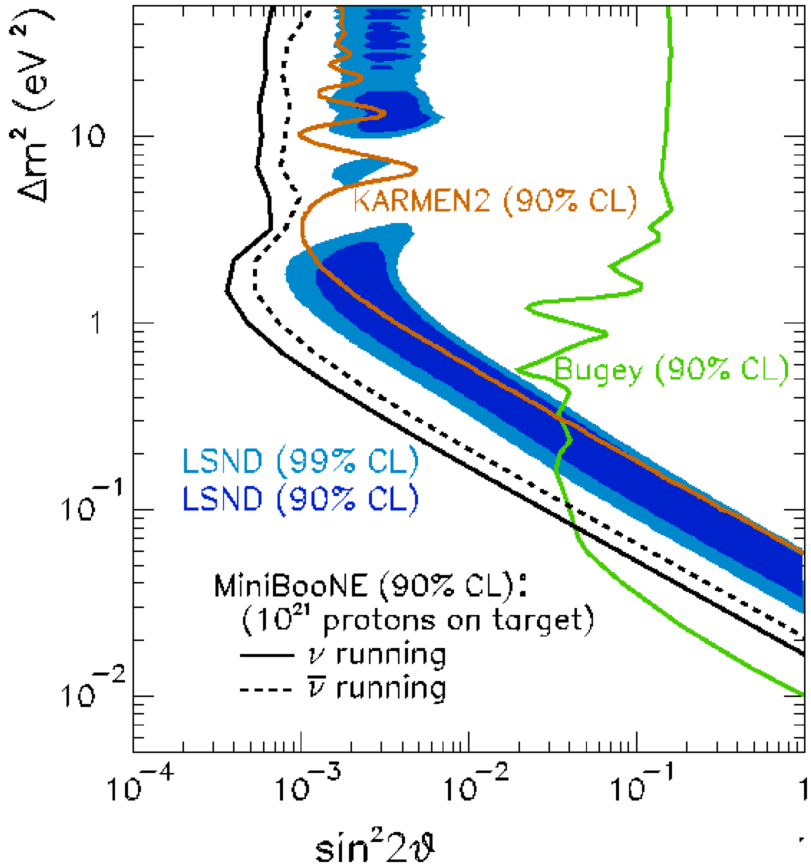
500 μ mis-ID



500 π^0 mis-ID



1000 LSND-based $\nu_\mu \to \nu_e$



cover LSND allowed region at 5 σ

updated estimates coming

currently expect results in 2005

Conclusions

steadily taking data

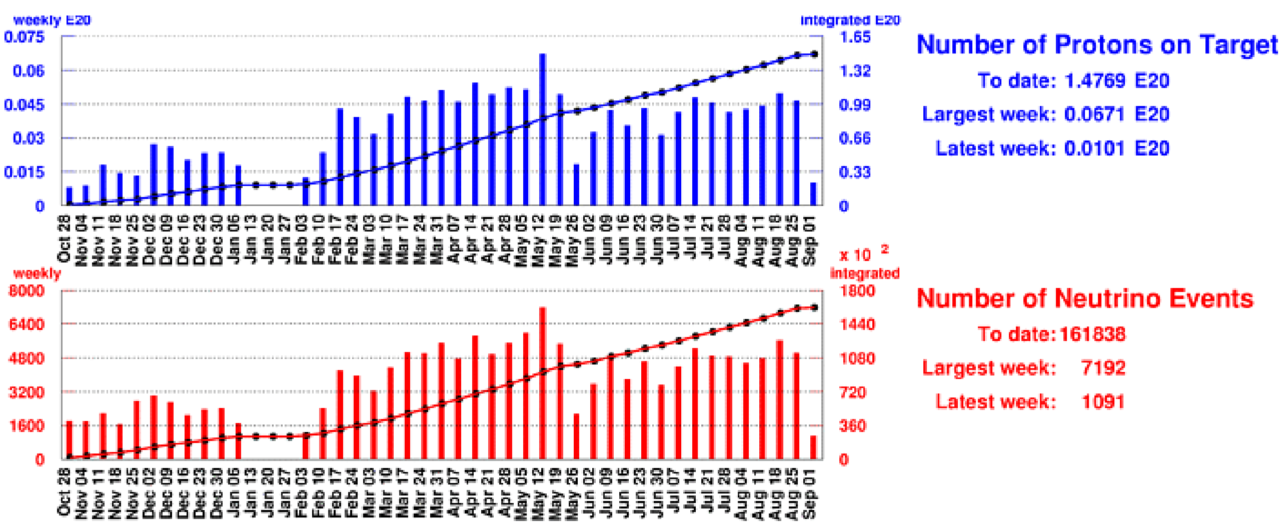
currently at 15% of 10^{21} p.o.t

beam is working well, but still need higher intensity

improvements underway (shutdown) will be key

first sample of neutrino physics

detector and reconstruction algorithms are working well



Detection and Reconstruction of Events

Charged particles in the mineral oil emit

Cherenkov radiation
- prompt
- in cone (θ_c=47.4^o for $\beta\sim$1)
- $\propto$ path above threshold

Scintillation light
- emission time constant ~ 18 ns
- isotropic
- $\propto$ kinetic energy

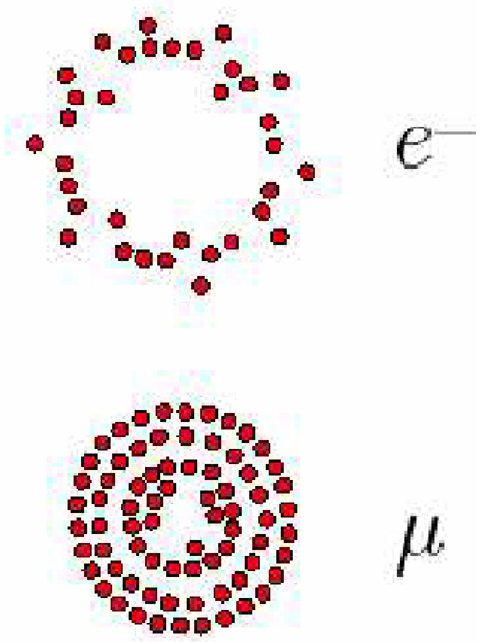
Fuzzy vs. sharp Cherenkov ring

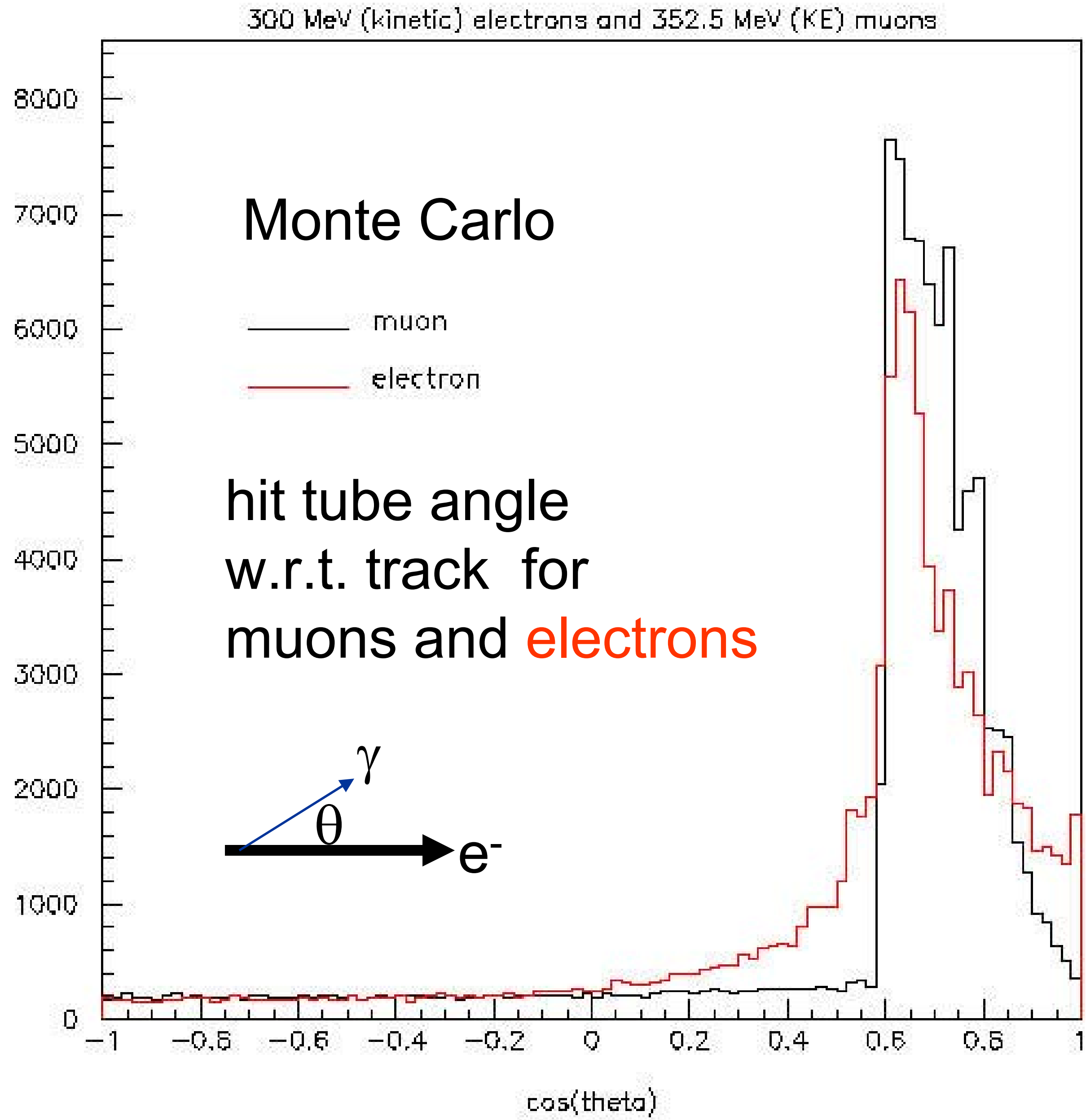
particle ID

Ratio of prompt to late light

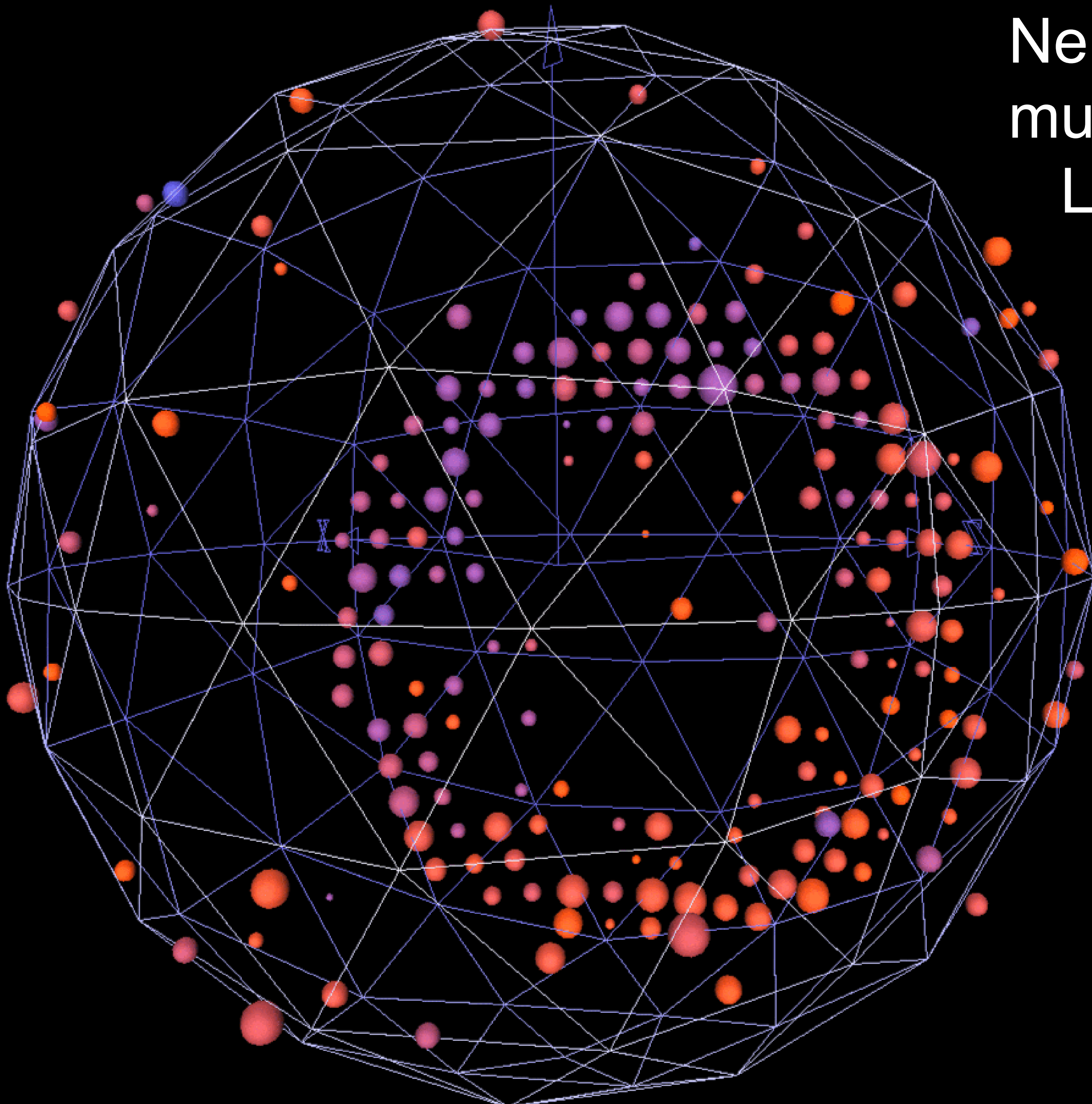
In pure mineral oil, Cherenk:scint ~ 3:1

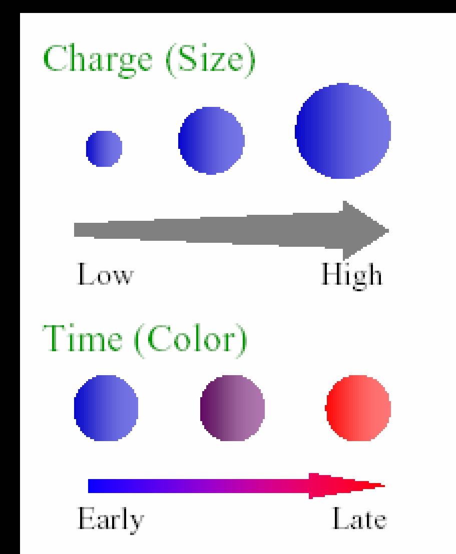
electrons are fuzzy
muons are sharp

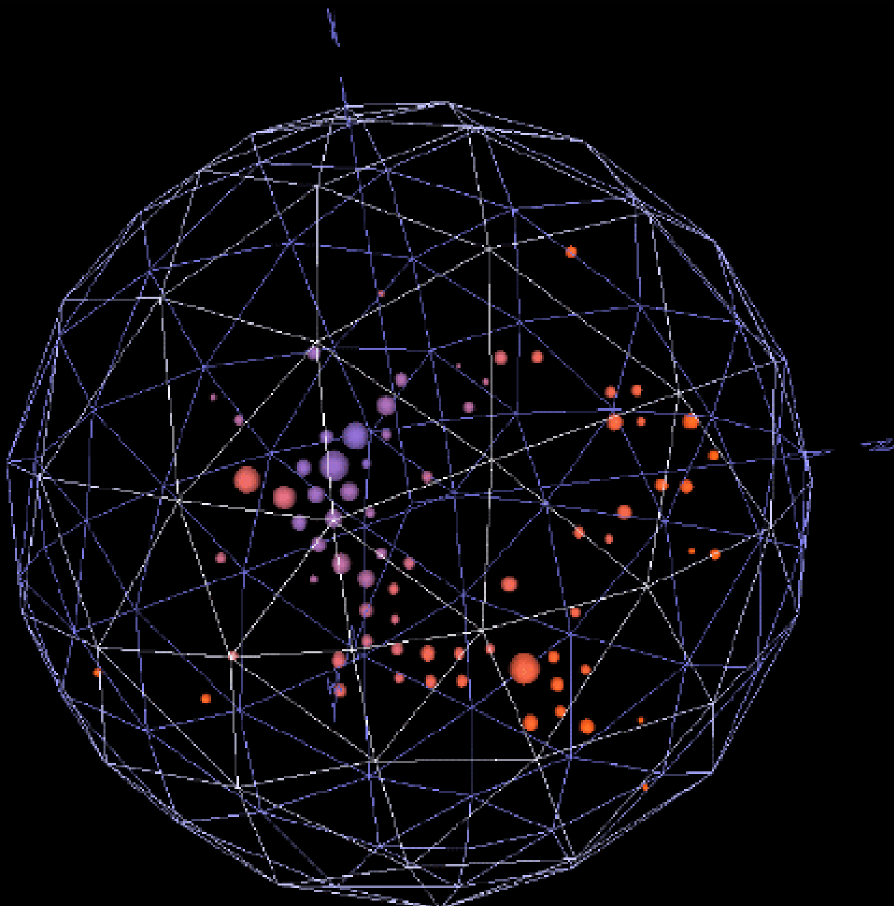




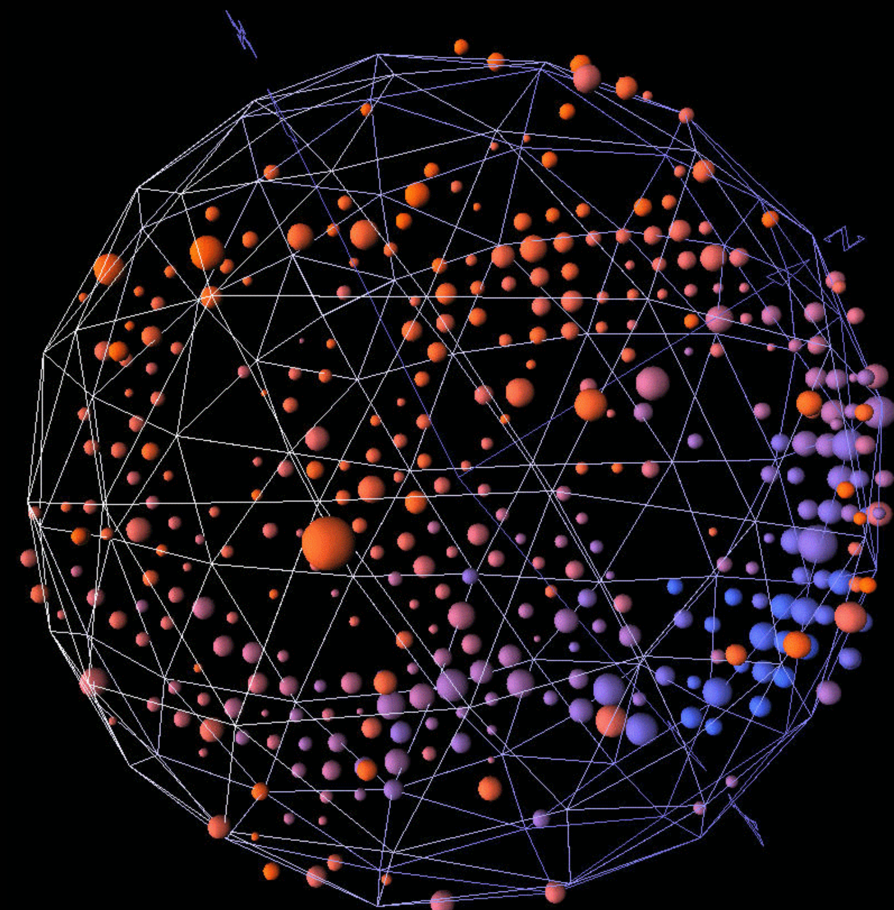
Neutrino-induced muon candidate Labor Day Weekend 2002





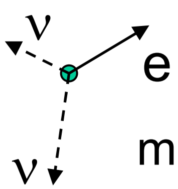


Electron from decay
of neutrino-induced muon



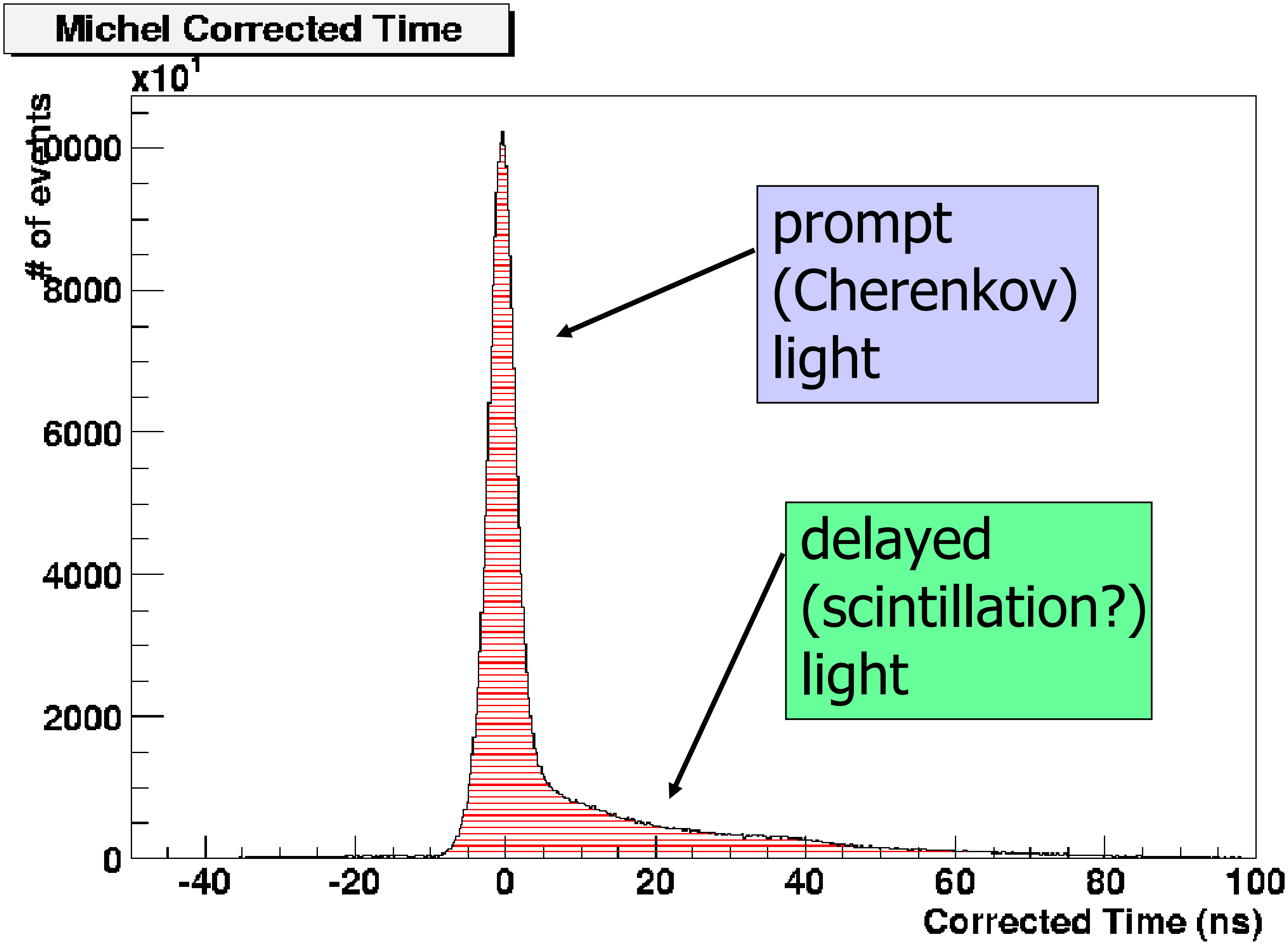
π^0 candidate

Time spectrum of light from Michel electrons

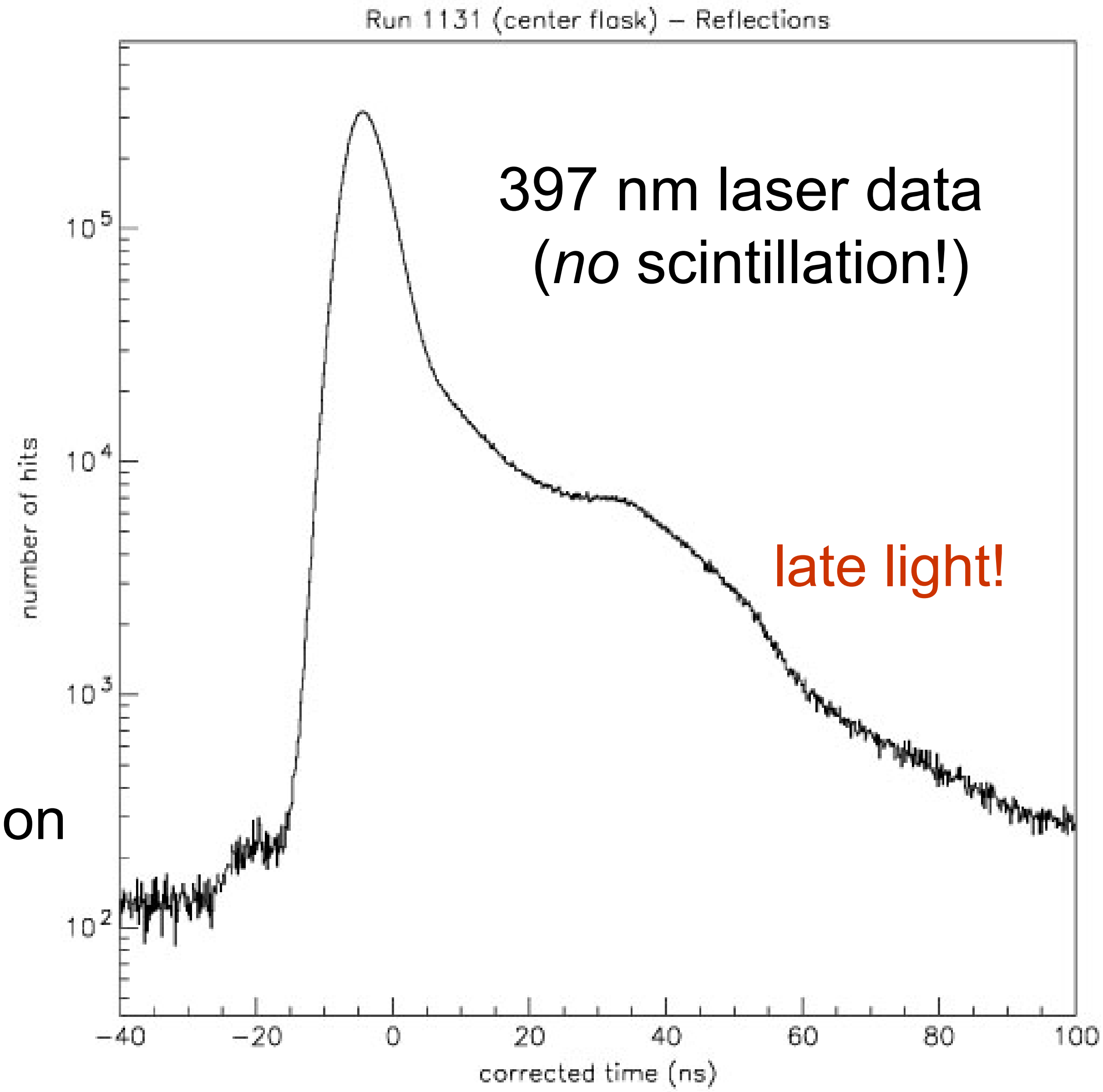


muon stops and decays

Measure, e.g., time resolution
scintillation time constant

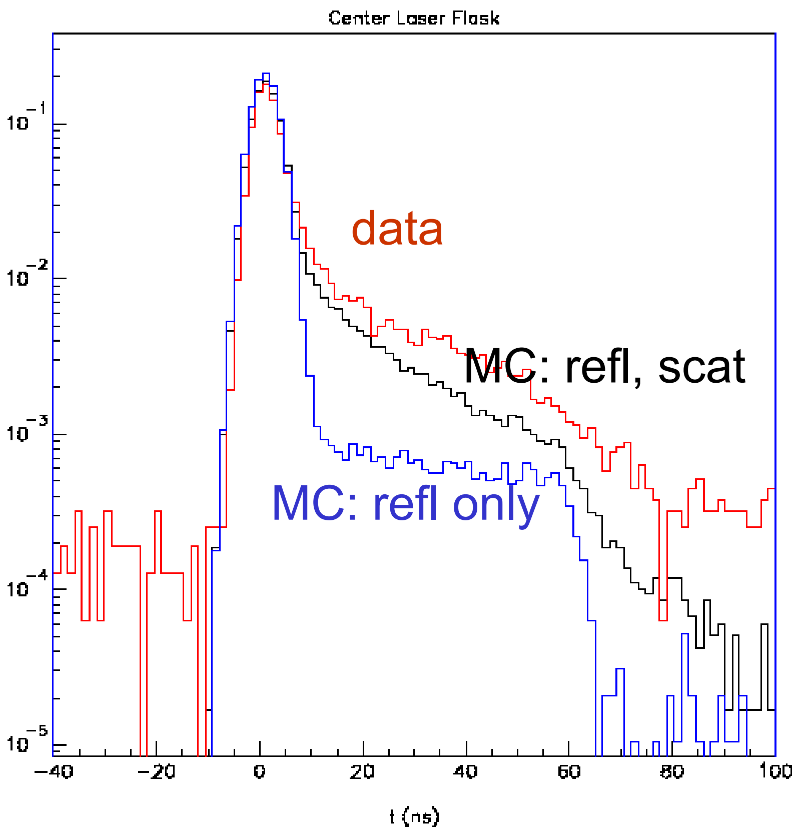


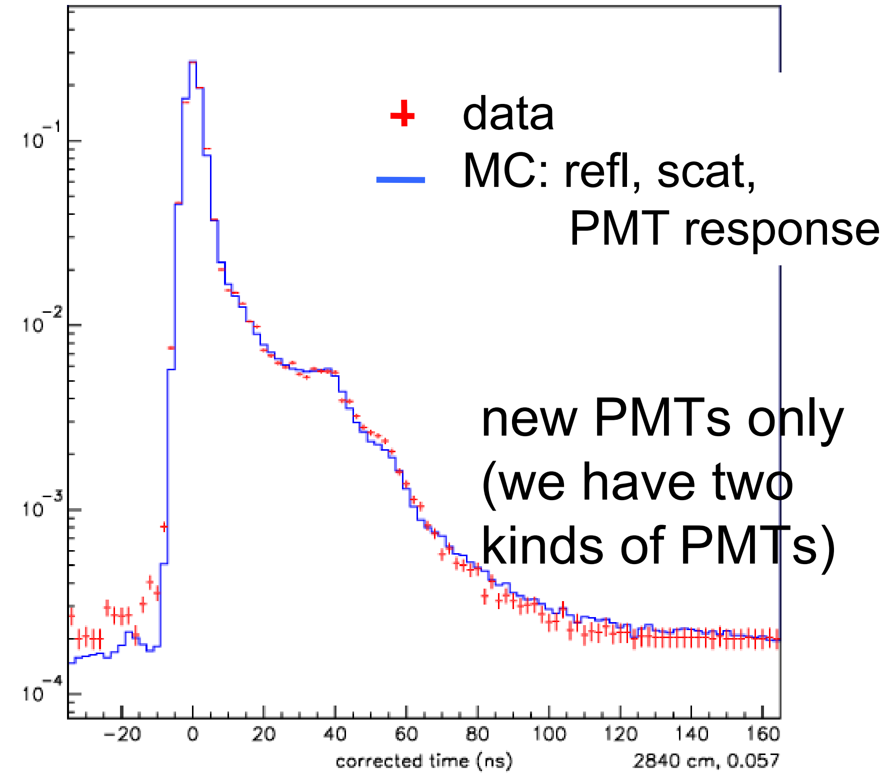
Or is it?



low energy laser photons should not induce scintillation

Modeling "late light"

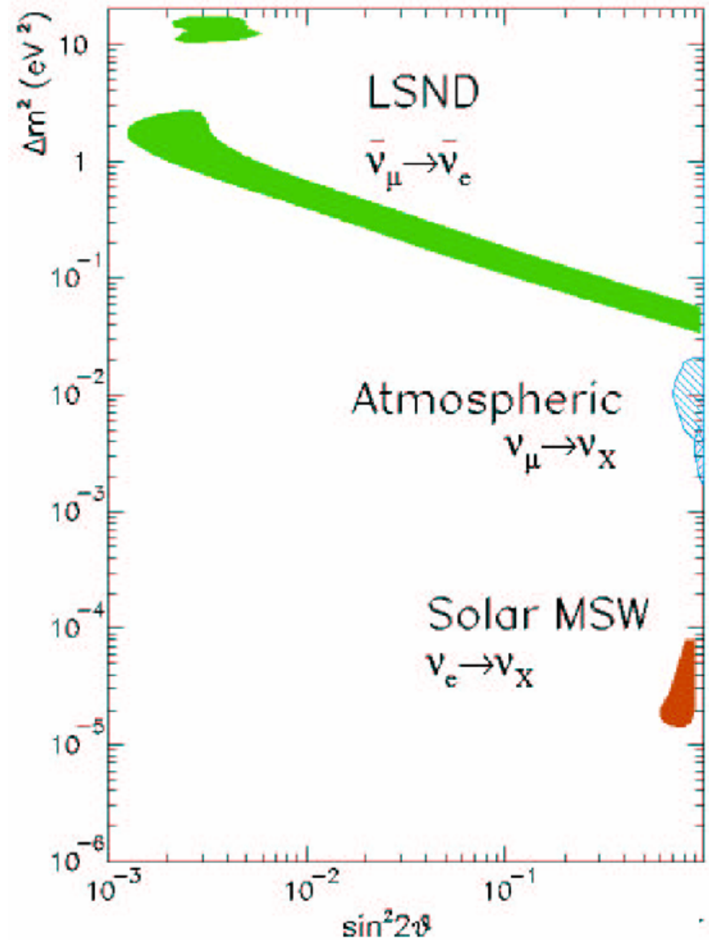




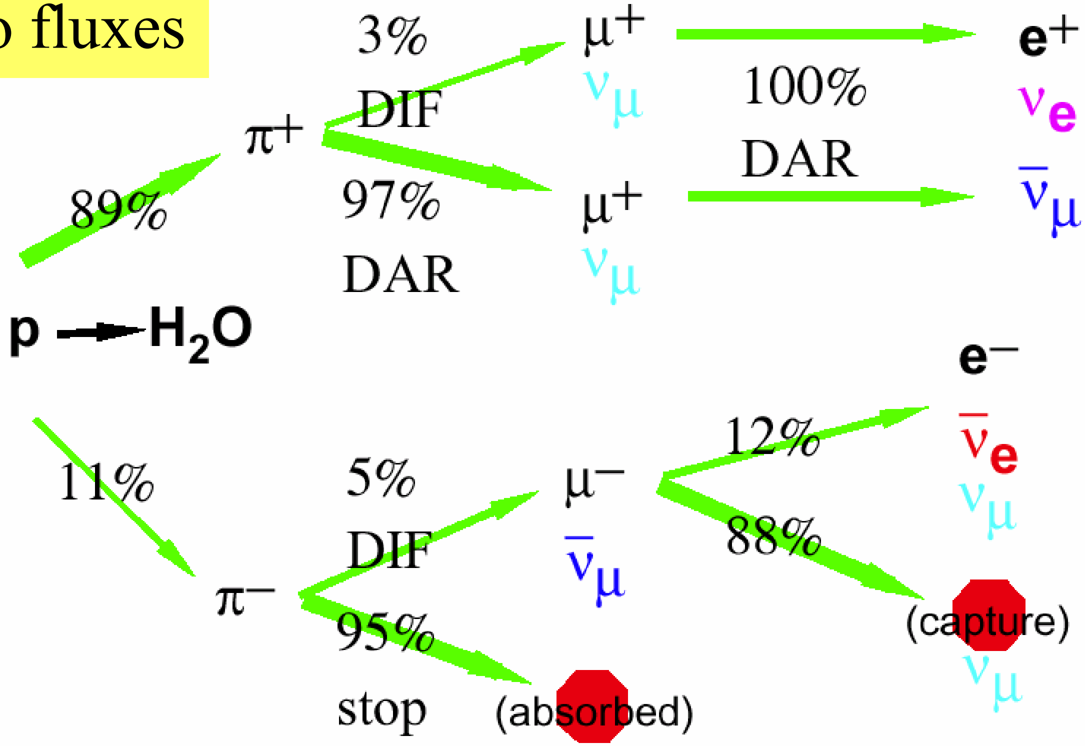
…and scintillation will sit on top of this

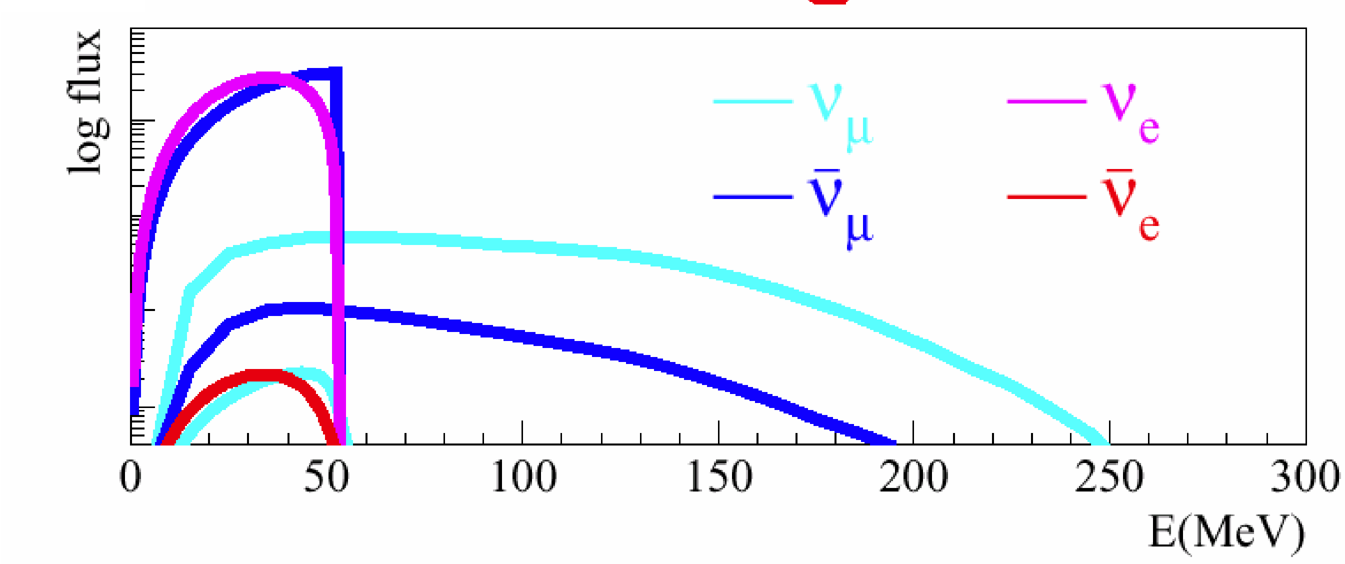
Oscillation Evidence

Setup	E	L	Δm^2 (eV^2)
Solar (+Reactor)	3 MeV N.B. matter (MSW) effects	1.5×10^{11} m	2×10^{-11} Best: 7×10^{-5}
Atmospheric (+Long Baseline Accelerator)	500 MeV-1 GeV	20-12000 km	Best: 2.5×10^{-3}
LSND	30 MeV	30 m	1



LSND
neutrino fluxes





μ^+ DAR

search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Largest backgrounds:

$\bar{\nu}_e$ from μ^- decay

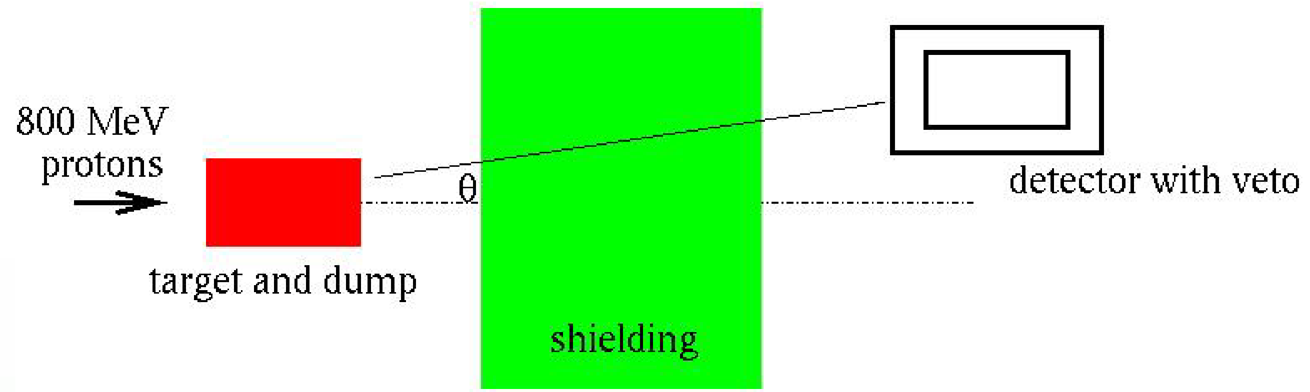
$\bar{\nu}_\mu$ from π^- decay

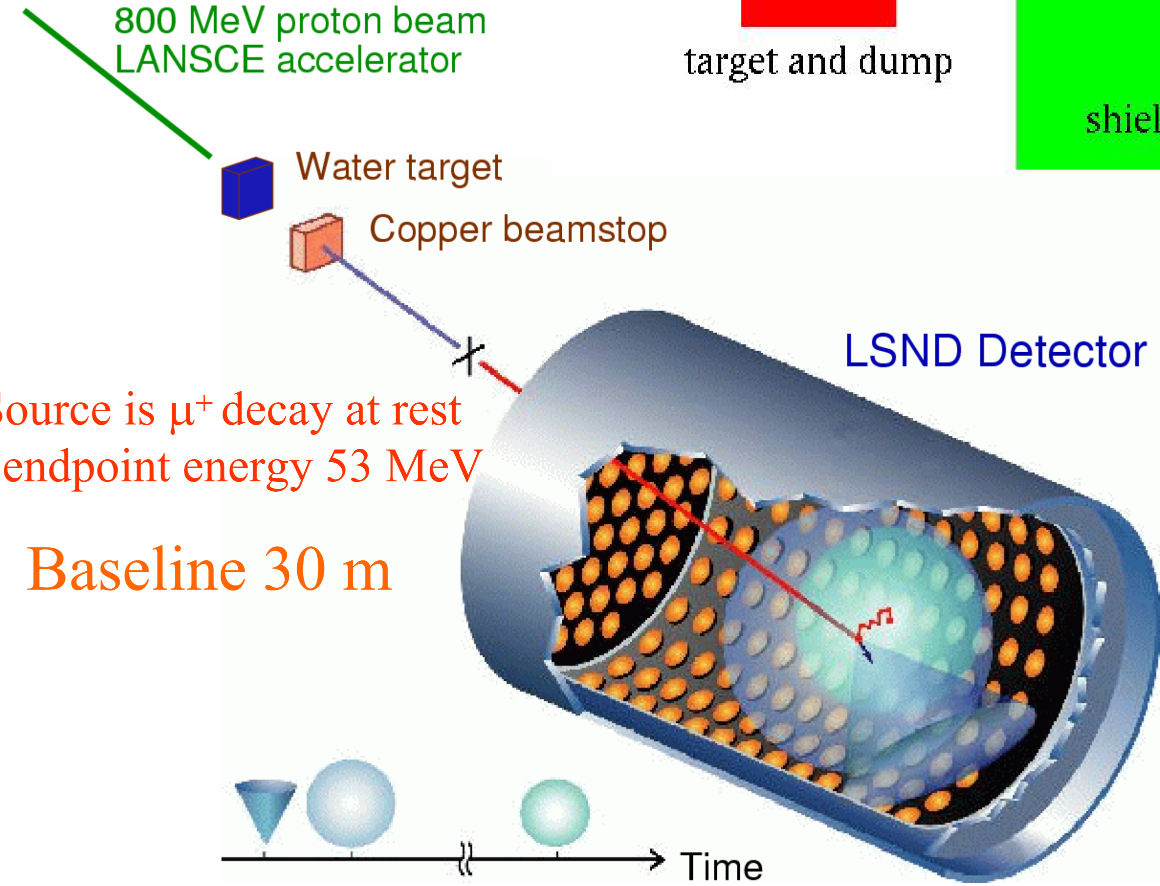
Also π^+ DIF

search for $\nu_\mu \rightarrow \nu_e$

Largest backgrounds:
cosmics

LSND (1993-1998)





Source is μ^+ decay at rest
endpoint energy 53 MeV

Baseline 30 m

Particle id via Cherenkov and scintillation light

$$\bar{\nu}_e p \to e^+ n$$

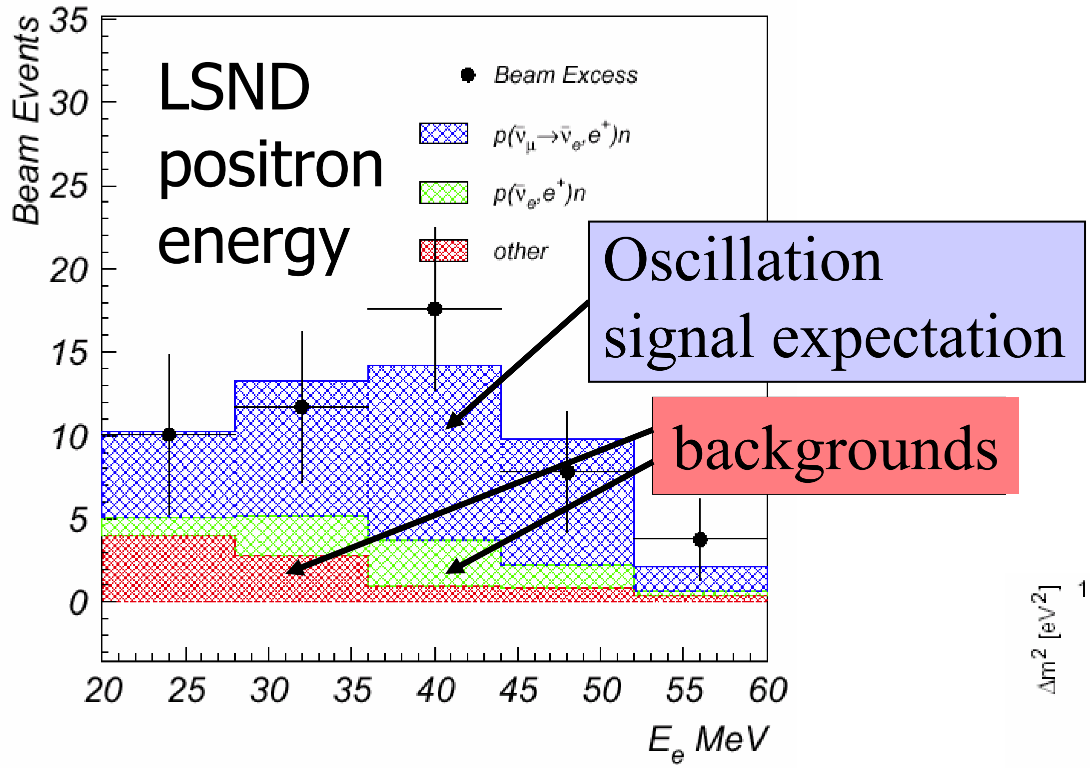
detect prompt e track,
$20 < E_e < 60$ MeV

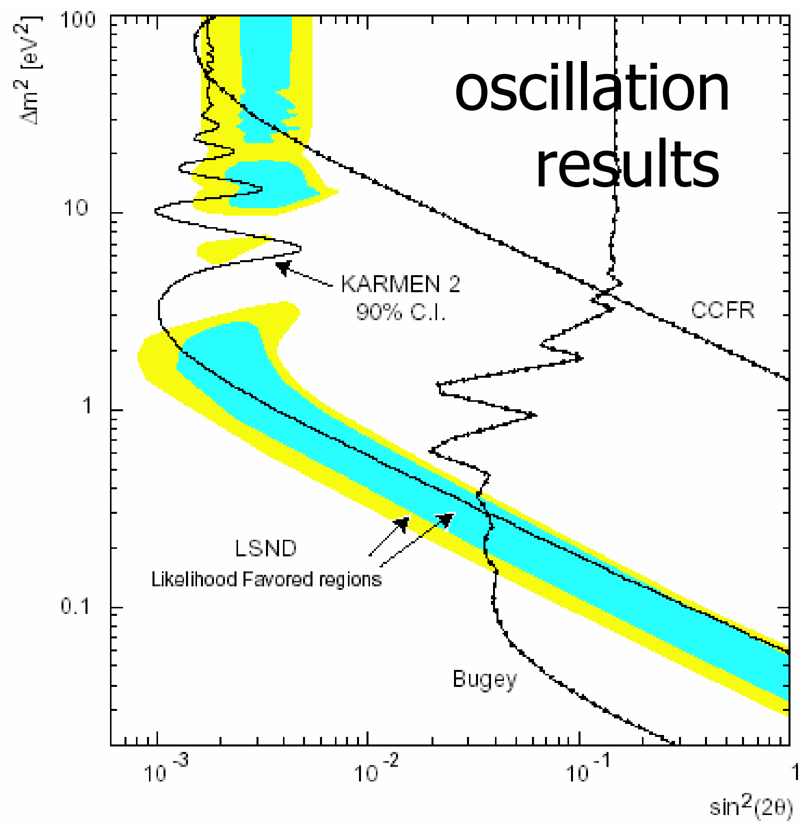
neutron capture:
$np \to d\gamma$ 2.2 MeV

γ correlated in position and in time with e
no B-field, signature is e and γ sequence

LSND and KARMEN search for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

Source is μ^+ decay at rest endpoint energy 53 MeV





LSND

Signal above background:

87.9±22.4±6.0 events

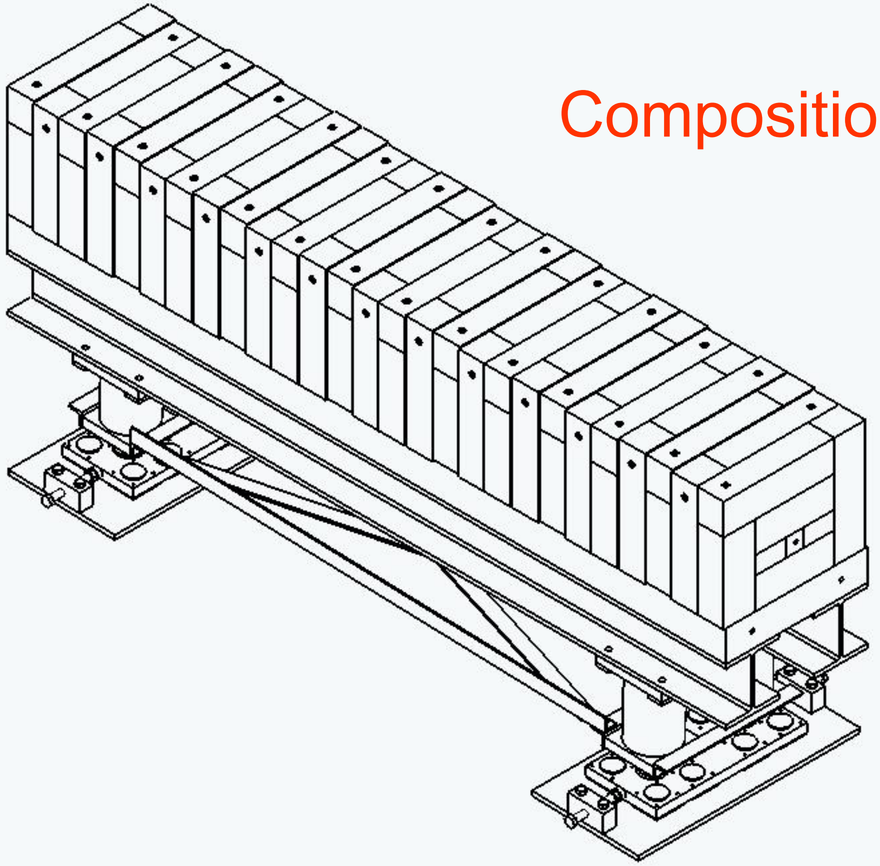
Oscillation Probability:

(0.264±0.067±0.045)%

KARMEN 2

Excludes part of LSND region

The LMC collimator



Dimensions: 81 inches long and
16 x 16 inches wide

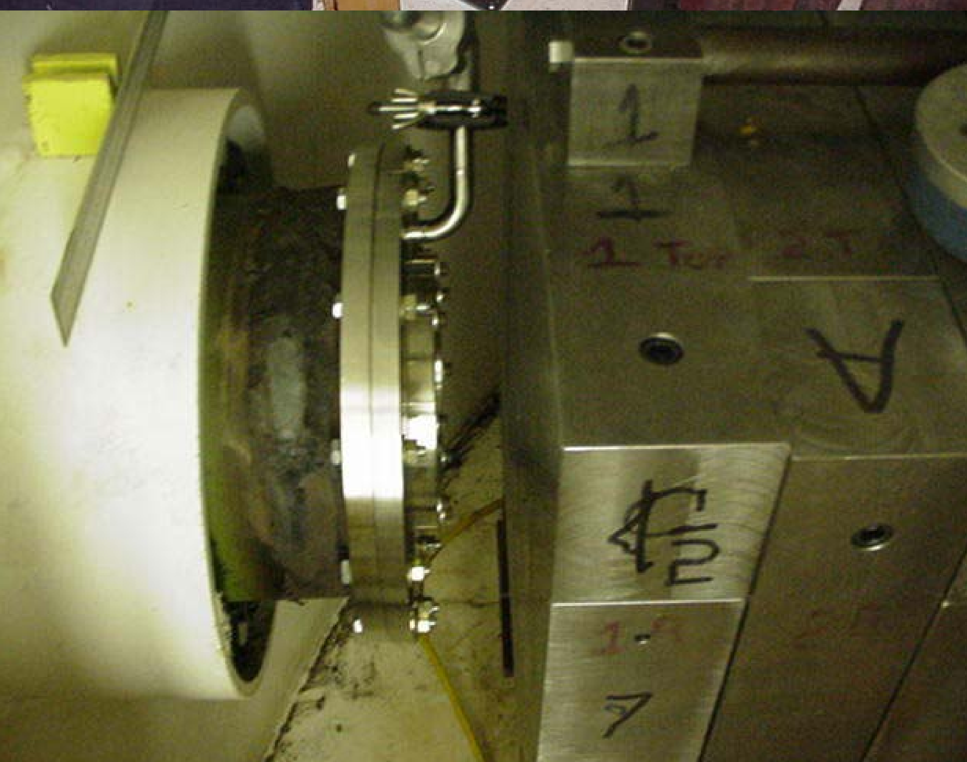
Composition: Steel with 2 x 2 inch
tungsten core

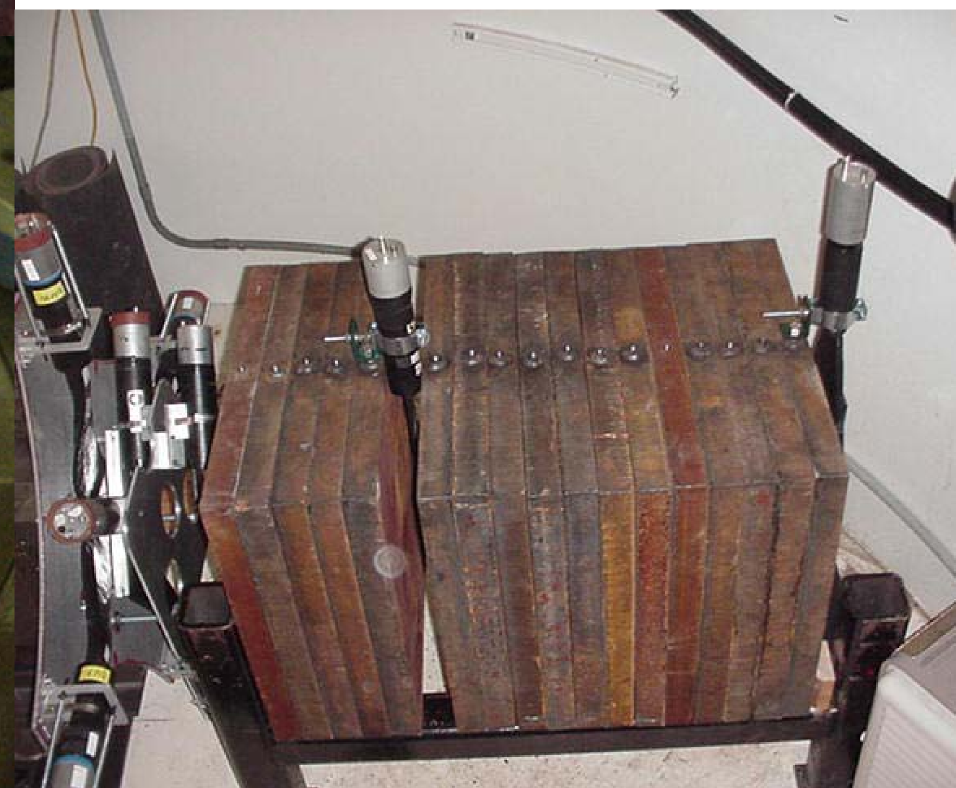
Weight: 3 tons

Aperture diameters:
from 0.6 cm upstream
1.0 cm downstream
in 27 steps

January 2003:

LMC collimator and temporary detector installation





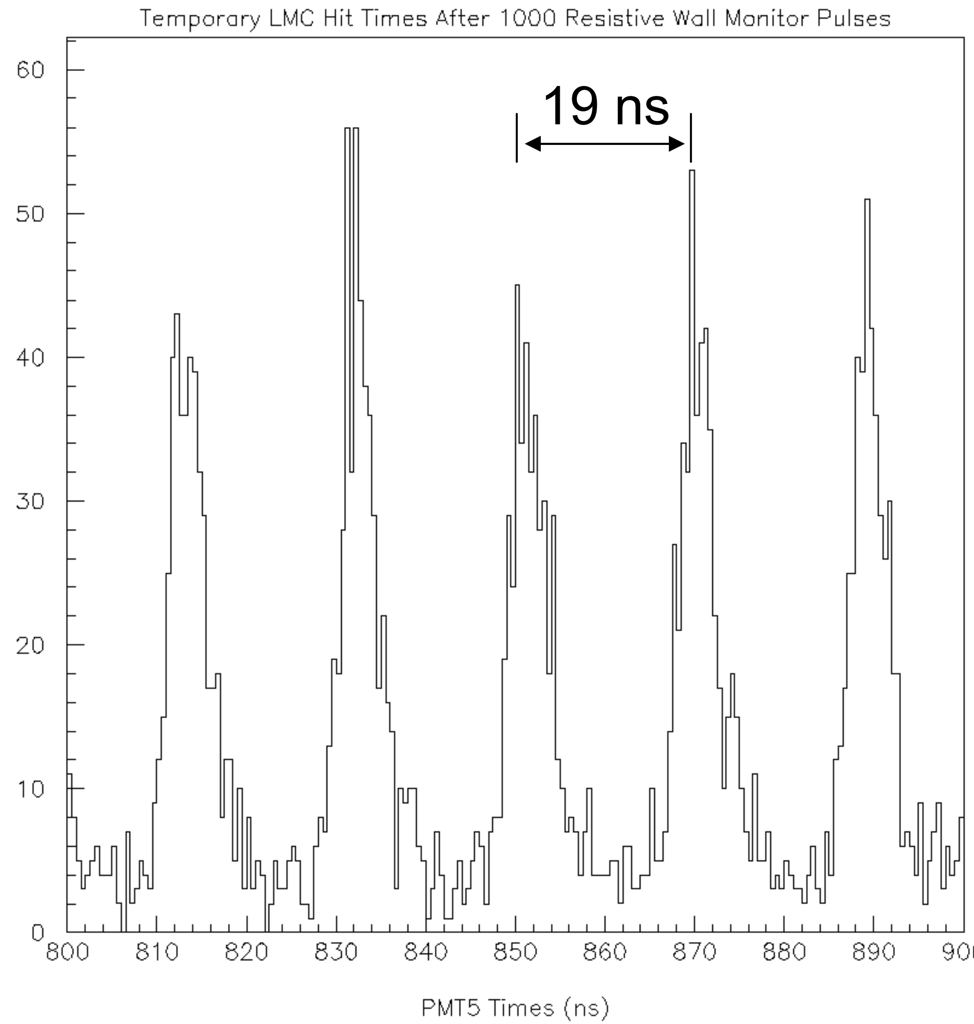
early LMC data

Booster delivers protons on target

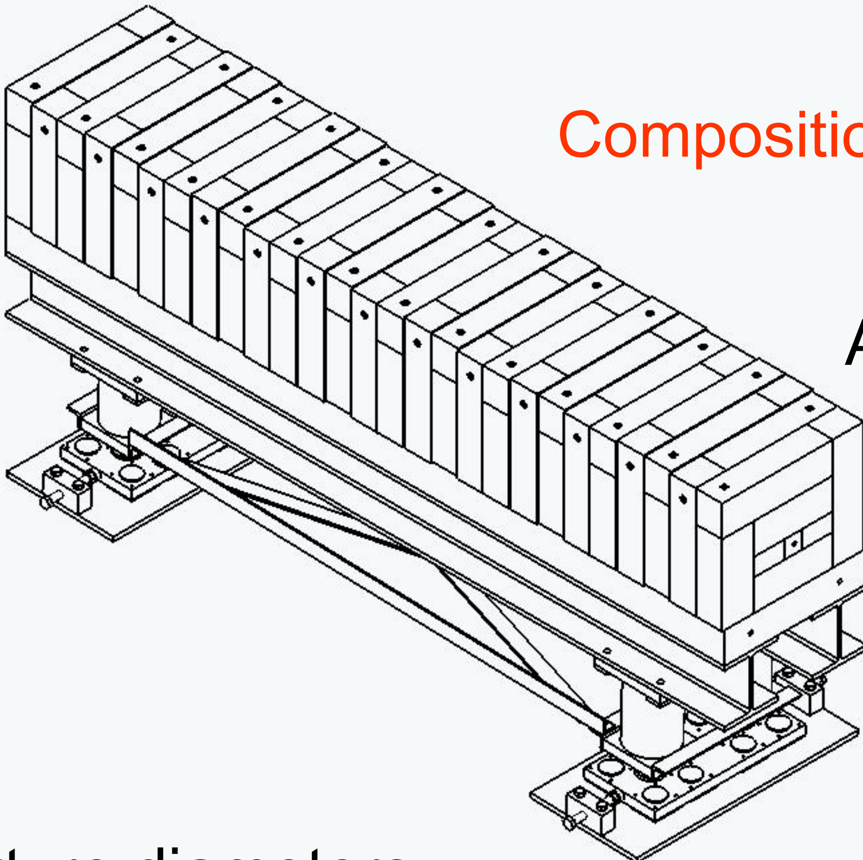
over a 1.6 μs spill

with a microstructure of 80 “buckets” separated by 19 ns

Signal at LMC displays this structure



The LMC collimator



Dimensions: 81 inches long and 16 x 16 inches wide

Composition: Steel with 2 x 2 inch tungsten core

Assembly: 27 3-inch-long modules

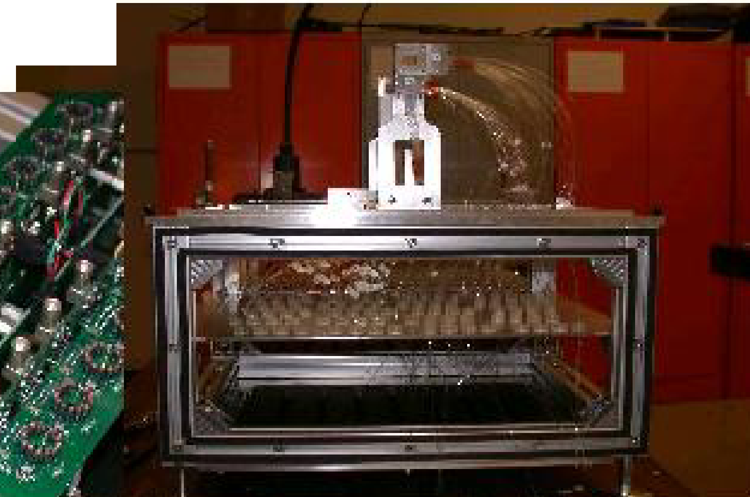
Angle from the floor: 1.82 degrees

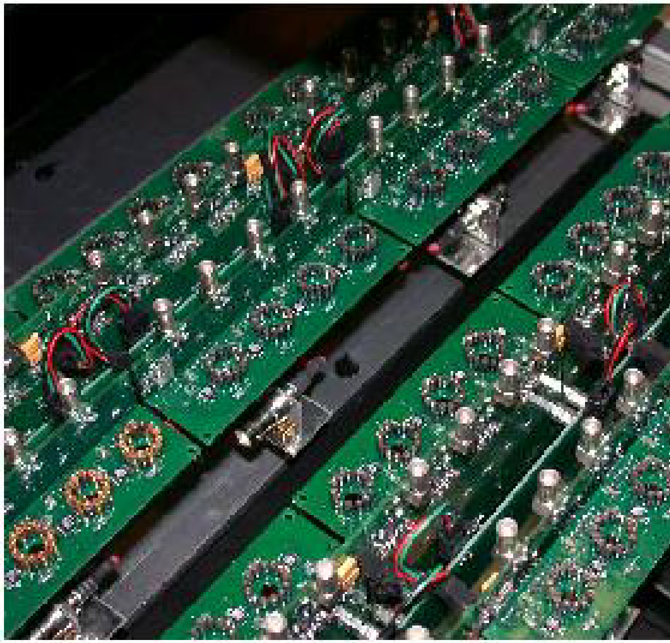
Weight: 3 tons

Aperture diameters:

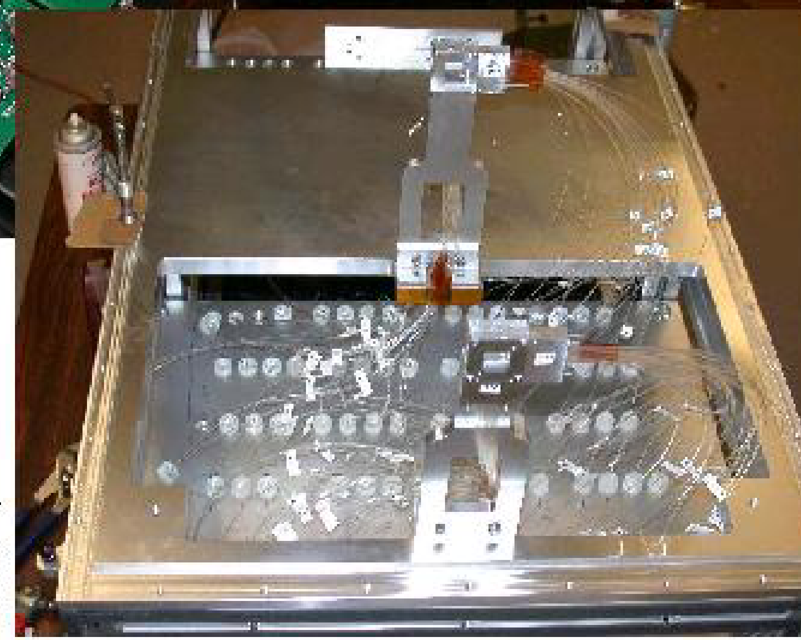
module 1: most upstream, 0.236 inch (0.6 cm) diameter aperture
module 27: most downstream, 0.392 in (1.0 cm) diameter aperture
Aperture diameter increases 0.006 inches in successive modules.

LMC fiber tracker under assembly
Jan 2003





PMT BASES



LIGHT
GUIDE
FIBERS

Ready to install
mid-March 2003